ERRATA and ADDENDUM

pg. 2, para. 2: 'climate affecting' for 'climate effecting'
pg. 4, para. 1: 'If they consume energy efficiently…' replaces 'If they consume energy efficiency…'
pg. 5, para. 1: 'The study data is from average Australian operations…' replaces 'The study data uses average Australian operations…'
pg. 8, footnote: Mebratu, D. (1998), 'Sustainability and Sustainable Development: Historical and Conceptual Review', *Environmental Impact Assessment Review*, Volume 18, pp. 493–520.
pg. 13, para. 2: 'would be affected' for 'would be effected'
pg. 17, para. 2: '…discrete sources of information…' replaces '…discreet sources of information…'
pg. 25, para. 3: '…sustainability concept models has its own goals…' replaces '…sustainability concept models has their own goals…'
pg. 29, para. 2: 'most likely follow existing' for 'most likely following existing'
pg. 31, para. 4: Added to sentence 'For example, coal fuelled…': Footnote: 'Other factors, primarily environmental legislation, also hastened this fuel transition from coal to oil.'
pg. 39, figure: replacement of figure with Figure A.
pg. 43, Section 2.4.4: '…shows the impacts previous sustainability assessments, reviewed in Section 2.4.3, have highlighted as important' replaces ' shows the impacts determined to be important in previous sustainability, environmental, economic and social assessments from the review in Section 2.4.3' and 'Many impacts measured by indicators…' replaces 'Most indicators…'. The following replaces the paragraph beginning 'Many of the indicators…':
'Tables 2.3.5 and 2.3.6 include many more indicators than Table 2.4.1. Many of these additional indicators measure the sustainability of an industry's corporate philosophy (e.g. the Human Rights and Society categories of indicators in Table 2.3.5 and the Voluntary actions, Human-capital, Ethics and Welfare categories of indicators in Table 2.3.6). For a proposed system, the choice of technology is unlikely to affect business philosophy. This may not be valid if the choice results in the use of materials sourced from companies with radically different business philosophies (for example, when deciding between purchasing from companies with very different worker conditions). Moreover, many of the remaining additional indicators measure differences in product quality (i.e. the Product Responsibility category of indicators in Table 2.3.5 and Environmental Efficiency category of indicators in Table 2.3.6). Electricity as a product does not vary with its source technology. Thus, its qualities (i.e. endurance, strength, durability, etc.), and indicators measuring quality differences, also do not vary.'
pg. 45, para. 3: 'using environmental, economic and social indicators and adopting a full "life-cycle" perspective' replaces 'using sustainability indicators and a "life-cycle" perspective'
pg. 49, para. 4: 'substance flow analysis' replaces 'substance flow'
pg. 51: 'Life Cycle Assessment' replaces 'Life Cycle Analysis' in title of Section 3.2.2.3. Both terms have been widely accepted for LCA.
pg. 52, para. 2: 'The LCA method is largely scientific' replaces 'The LCA method is scientific' and 'In contrast, results using EIA are influenced by local legislative requirements.' replaces ', without the EIA method's limiting local legislative requirements.'
pg. 56, para. 2: 'Documentation of these criteria' replaces 'Documentation of this criteria'
pg. 62, para. 1: 'The choice of CF factors, from these sets, introduces…' replaces 'The choice of CF factors introduces…'

CONTINUED IN ENDPAGES

SUSTAINABILITY OF ELECTRICITY GENERATION USING AUSTRALIAN FOSSIL FUELS

by

John R. May B.E.

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Dr. David J. Brennan

Department of Chemical Engineering
Monash University
PO Box 36
MONASH UNIVERSITY VICTORIA 3800
AUSTRALIA

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ABSTRACT

The reliable and inexpensive supply of electricity is crucial to the development of any nation's economy and the welfare of its population. The prevalent forms of electricity generation in Australia, which consume Australia's abundant black and brown coals and natural gas, have some negative effects on its environment. Furthermore, exports of Australian black coal and natural gas (as LNG) fuel other nations' electricity generation systems, affecting their economies, social welfare and environment. One Australian fossil fuel, brown coal, has a poor reputation, based on high CO_2 emissions from its combustion. Using the same basis, natural gas has a good reputation. Yet, testing of these reputations with respect to their combined environmental, economic and social performance, or sustainability, has not occurred. Therefore, this thesis develops a method for quantifying the impacts on sustainability caused by generating electricity from Australia's abundant fuels supported by a detailed analysis of environmental impacts with key economic and social impacts.

A critical review of sustainability assessment finds no common or standardised method, although it finds that the use of indicators is essential for an objective, quantitative approach. The selection of life cycle assessment (LCA) for the environmental indicators enables the quantification of environmental impacts and the use of extended boundaries. Examined are several steps in the LCA method that cause difficulties during application, including allocation of impacts to products, analysis of uncertainty and the quantification of the resource depletion impact. Testing of several approaches for analysis of uncertainty establishes that separate qualitative and quantitative information is useful in describing the robustness of environmental indicators to uncertainties in data. The creation of an Australian resource depletion indicator enables the examination of the local implications of the consumption of resources. No previous methods for producing economic and social indicators allowed the use of extended boundaries, and thus modifications proved necessary. The extension of the optional LCA practice of normalisation to these indicators enables the comparison of the importance of each different type of impact using a scientific, value-free basis: comparative contribution to Australia's impact from all sources.

The assessed electricity generation systems feature: boundaries extended to include fuel mining and transport to the power station and electricity generation and delivery; electricity generation technologies currently used in Australia and some in development;

and electricity generation fuelled using exported Australian fuels. Data selected for the sustainability assessment of these systems, is from a critical review of an extensive range of data sources.

No one fuel has universally superior sustainability, or environmental, performance as measured using the indicators. However, the indicators of sustainability show that the natural gas systems, using the combined-cycle gas turbine electricity generation technology, are superior to the others for most of the indicators. Yet, various impediments to increasing consumption of natural gas (including its greater resource scarcity), limit Australia's ability to replace coal systems with these natural gas systems. While brown coal systems are generally inferior to black coal systems for climate change, brown coal systems outperform black coal systems for the majority of indicators. Advanced coal technologies are markedly better than the present conventional systems. However, they require substantial further development to become commercially viable. Systems using black coal have markedly poorer safety performance than do other fuels, due to their fuel mining and transport operations. Systems using the export fuels, LNG and black coal, have substantially greater impacts on sustainability, than do domestic systems with the same electricity generation technology. The normalised indicators show that capital expenditure is of greatest importance when comparing different electricity generation systems.

The indicators of sustainability developed have major implications when considering additions, or modifications, to existing electricity supply networks. The developed sustainability assessment method is adaptable for use in other industry and product systems.

CANDIDATE'S CERTIFICATE

This is to certify that this thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other institution. Additionally to the best of my knowledge, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

[redacted]

John May

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1. INTRODUCTION

'There is no way to make brown coal environmentally viable for energy production'

BROWN COAL SHOULD BE FINISHED AS A FUEL, GOVERNMENT TOLD

– THE AGE (MELBOURNE, AUSTRALIA) 18/6/02

1.1 FOSSIL FUELS, ELECTRICITY GENERATION AND SUSTAINABILITY

Energy is necessary for daily survival (WCED (1987)). It provides heat for warmth, cooking, and manufacturing, or mechanical power for work and transport, without which we could not support our way of life (WCED (1987)). In our society, electricity is the most pervasive energy provider, delivered to almost every home and business*. Thus, the reliable and inexpensive supply of electricity is crucial to the development of any nation's economy and the welfare of its population.

Australia has an abundance of many fossil fuels. Coal in particular, with 90 billion tonnes, or 9 % of world reserves (as at June 2000) within Australia (BP (2000)). Natural gas resources are also large, with over 44 x 10^{12} cubic feet, or 0.9 % of world reserves, within Australia (BP (2000)). Moreover, the extraction of these fuels is inexpensive, as it is necessary to use only the most easily recoverable reserves. Consequently, the utilisation of these fuels was favoured when planning Australia's electricity generation network. In 1999, over 90 % of Australian electricity generation used these fuels (Electricity Supply Association of Australia (1999)). Of this amount,

* Electricity consumption once contributed only 4% of energy, in the 1930's (OECD (1985)). By 2000, it had risen to become a major contributor, 36 % of energy in 2000 (IAEA (2000)).

55 % used black coal, 30 % brown coal (or lignite) and 5 % natural gas (Electricity Supply Association of Australia (1999)). Imbalances in the distribution of these resources, coupled with the fragmented development of the Australian electricity supply, have resulted in the use of different fuels in different states. The major black coal resources are in New South Wales and Queensland, and thus over 90 % of electricity generation uses this fuel in these states. Similarly, over 90 % of electricity generation in Victoria uses brown coal (Electricity Supply Association of Australia (1999)). In South Australia and Western Australia, natural gas is more abundant than coal, and thus much of the electricity generation uses natural gas. Therefore, each Australian State has its own inexpensive fossil fuel as an energy source for electricity generation.

The combustion of fossil fuels releases a wide range of substances into the environment. Many of these substances have harmful effects on fauna and flora, and significantly on the earth's temperature and climate. Electricity generation is a proportionally large consumer of fossil fuels within Australia, when compared to most other consumers (ABS (2001a)). Thus, electricity generation is a major contributor to these effects. It accounts for over one third of climate effecting gases ('Greenhouse Gases'), and substantial proportions of the acidifying gases sulphur dioxide and nitrogen dioxide (AGO (1999)). A similar pattern occurs in other countries with similar electricity generation systems, e.g. U.K (see DoE (U.K.) (1997)) and U.S.A. (see EPA (U.S.A.) (2000)). Therefore, the assessment of these negative effects, as well as benefits to our economy and social welfare, is essential when evaluating the net benefit (or harm) of electricity generation using fossil fuels.

The sustainability concept specifically considers impacts on the environment, economy and social welfare. The sustainability concept has many different definitions. The basis for most is the oft-quoted statement from the Brundtland report (WCED (1987)): 'To meet the needs of the present without compromising the ability of future generations to meet their own needs'. Disagreements surround proposals of measures of present sustainability, and methods for attaining long-term sustainability. Contentious also is the question of how to recognise the attainment of sustainability. However, all agree that the goals for sustainability are the minimisation of all negative impacts and maximisation of all positive impacts on the key areas of the economy, the environment, and social welfare.

Electricity, when consumed, produces no direct negative economic, environmental or social impacts at its point of use. It may thus be an ideal energy source for a sustainable society (Schaap (2000)). Indeed the supply of electricity has since its introduction, enhanced both economic and social welfare, by redistributing employment and social services, between urban and rural areas, and increasing the general standard of living (IAEA (2000)). The sustainability concept requires that future generations have access to these same benefits. Nevertheless, as is earlier intimated, electricity generation has negative sustainability impacts (IAEA (2000)). Therefore, to maintain electricity as an energy provider for sustainability, these negative sustainability impacts must be minimised or removed.

Electricity generation involves the conversion of energy contained in fossil fuels, plants, animals, atomic fission, sunlight, wind, or water. The conversion from energy source to electricity is unique for each. Consequently, the types and magnitudes of effects on sustainability (sustainability impacts) caused by each will be unique (WCED (1987)). In addition, it is possible to use different technologies for this conversion. The choice of technology also modifies the type and magnitude of the sustainability impacts resulting from the conversion. Thus, by nominating a particular energy source and technology combination, a corresponding range and magnitude of sustainability impacts will occur (WCED (1987)). Therefore, assessment of each possible energy source and technology option is necessary to reduce the negative sustainability impacts of electricity generation for Australia.

Traditionally, analys~~i~~es of individual impacts have utilised physical boundaries, and thus a traditional assessment of the environmental or economic impacts of electricity generation would consider the electricity generation plant and its immediate environ~~s~~ment. Inherent in this method is an assumption that the electricity generation plant is not responsible for any of the impacts caused by other industries and electricity consumers. However, this assumption is false. Each electricity generation plant generally consumes an energy source obtained off site and materials produced in different industries. Similarly, its construction, commissioning, decommissioning and demolition, use materials, energy, and equipment produced in different industries. All of these different industries rely on the electricity generation plant to consume their products, and are thus dependent on its existence. Consequently, the electricity generation plant is responsible for a proportion of the impacts caused by these dependent industries. Electricity consumers can consume electricity both efficiently and inefficiently to meet a need (i.e. to heat a room). If they consume electricity inefficiency, a greater amount of electricity will be necessary to meet this need, than if they had consumed electricity efficiently. Generation of this additional electricity will result in greater impacts from the electricity generation plant. If the electricity generation plant has a responsibility to ensure the consumption of its product is efficient, then it is responsible for a proportion of the impacts caused through this inefficiency. The inclusion of these proportions of impacts from dependent industries and product use is known as the 'life cycle' perspective, and is of increasing interest in both environmental and sustainability analysis (Azapagic and Perdan (2000), Cowell *et al.* (1999)).

The use of brown coal, often branded a 'dirty fuel', for electricity generation, has come under particular scrutiny, far more so than do other Australian fossil fuels. Many quotes similar to that provided at the start of this chapter appear in newspapers and reports. The basis for this branding is the comparatively greater emissions of 'Greenhouse Gases' from power stations consuming this fuel. Meanwhile, for natural gas and black coal, other groups have reported varying findings over their relative 'Greenhouse Gas' emissions from electricity generation. For example, the Australian Gas Association, in the context of greenhouse gas emissions, state (AGA 2002): '*In mainstream electricity generation, power stations fuelled by natural gas are far cleaner than those burning oil, black coal, or brown coal.*' While the Australian Coal Association state (BHP Minerals Technology (2001)): '*On a full life cycle basis, gas-based electricity generation may have similar or even higher greenhouse gas emissions than coal-based generation.*' The basis for these claims is only one type of negative effect, greenhouse gas emissions. Therefore, these claims may misrepresent the actual impacts of electricity generation using these fuels. Only a sustainability assessment, including all positive and negative effects, can estimate these actual impacts.

1.2 AIM AND SCOPE

Consequently, the aim of this thesis is to assess the relative impacts on sustainability of electricity generation systems, consuming Australian brown coal, black coal and natural gas fossil fuels, and utilising a 'life cycle' perspective.

The study includes fossil fuels prevalent in Australian electricity generation (black

and brown coals, and natural gas) and exported in large quantities for electricity generation (black coal and LNG). The comparison places greater emphasis on the assessment of environmental impacts, due to the desire to establish whether brown coal really is a 'dirtier fuel' than are black coal and natural gas. The bases for selection of technologies for electricity generation are: for currently available technology, common usage; and for proposed technologies, the authority of source and extent of potential benefits. The study data uses average Australian operations, rather than best case or particular plants, to ensure that the assessment conclusions are applicable throughout Australia.

1.3 OVERVIEW OF THE STUDY

Chapter 2 examines sustainability, discusses options for its measurement and establishes which method has greatest advantages. Then, this chapter critically reviews assessments of major negative and positive effects from electricity generation, to establish which effects must be included in the assessment of sustainability.

Chapter 3 reviews methods for quantification of these important effects. It reviews the strengths and weaknesses of ~~the~~ life cycle assessment (LCA) as a tool ~~environmental method~~. In particular, it examines and proposes solutions for difficulties in: quantifying the effect of resource consumption; comparing different types of effects, through normalisation and weighting; and estimating the uncertainty of the quantified effect measures due to uncertainties in data, decisions and assumptions. It reviews methods for quantifying economic effects and proposes measures to overcome these method's shortcomings. Finally, it proposes some methods for quantifying effects on social welfare.

Chapter 4 details the steps necessary to quantify the sustainability effects of electricity generation using the methods of Chapter 3. It does this by, firstly, describing the types of electricity generation systems prevalent in Australia and equivalent systems consuming fossil fuels exported from Australia. Following each description, it provides the information necessary to use the methods of Chapter 3 on these systems. Finally, it presents other data and calculation steps necessary to quantify the sustainability effects and test the solutions proposed in Chapter 3 for dealing with difficulties in the LCA method.

Chapter 5 presents and examines the quantified effects for the electricity generation systems. Additionally, it presents the results of the tests of the proposed solutions to difficulties in LCA. It includes a unique plot of sustainability effects, using normalisation, which enables comparisons of the importance to Australia of contributions to the effects.

Chapter 6 discusses some implications of the sustainability assessment concerning the relative sustainability performance of the different fuels and types of electricity generation systems. Then, it discusses the advantages and limitations of the method developed for quantifying sustainability effects and the proposed solutions for difficulties when using the LCA method. Then, it discusses the possible use of the method in evaluating new systems, or replacing old systems, in electricity generation networks. Finally, is discusses the method's flexibility for assessing the sustainability of other product systems.

Chapter 7 identifies the conclusions and recommendations of the thesis.

Appendices 1 and 2 contain supporting information for Chapters 4 to 6, including tables of data sources and example calculations. Within this report are many abbreviations and industry-specific terms, which often have conflicting definitions in other literature. Therefore, presented are a list of the nomenclature and acronyms ('Nomenclature') and a glossary of terms ('Glossary'). Lastly, appears a list of references and other relevant literature.

Parts of this thesis, including the quantification of the environmental effects of electricity generation using LCA and the difficulty of estimating uncertainty in LCA, have been published in conference proceedings and journals (May and Brennan (2001, 2002, 2003a, 2003b)).

2. SUSTAINABILITY

'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs... The goals of economic and social development must be defined in terms of sustainability in all countries... Interpretations will vary, but... must flow from a consensus on the basic concept of sustainable development and on a broad strategic framework for achieving it.'

Our Common Future, WCED (1987), pg 43.

2.1 OVERVIEW OF SUSTAINABILITY

Assessing the relative impacts on sustainability of electricity generation systems requires an understanding of the concept of sustainability. Many different perspectives on the concept of sustainability had developed since the publishing of 'Our Common Future'* in 1987 (Board on Sustainable Development (1999)). Each of these perspectives represented a different understanding of what it meant to reach sustainability. These perspectives invited establishment of measures to assess progress towards sustainability. Reviewing these perspectives, and the measurement techniques thus derived, should indicate an appropriate methodology for the assessment of electricity generation systems.

Section 2.2 reviews the many perspectives on the concept of sustainability. Section 2.3, describes the measurement techniques developed from these perspectives, and reviews their use. Section 2.4 expands on the links, intimated in Chapter 1, between

* WCED (1987).

electricity generation and wider sustainability. Many studies have discussed one type of impact on sustainability for electricity generation systems, i.e. the environment. Thus, Section 2.4 also reviews these studies to indicate which impacts on sustainability are of most importance for electricity generation.

2.2 *DEFINING SUSTAINABILITY*

2.2.1 OVERVIEW OF DEFINING SUSTAINABILITY

An important outcome of Chapter 1 was the recognition that it is important to consider environmental, economic and social impacts to compare electricity generation systems. Sustainability assessment and sustainability impacts were the terms applied to this type of comparison and the range of impacts. For this reason it is important to review the concept of sustainability to define what it is, and what it is not, so that later discussions of the sustainability of electricity generation systems may be better understood.

Section 2.2.2 reviews the history of the concept of sustainability and the breadth of definitions. Section 2.2.3 then examines the reasons for the great number of sustainability definitions. Section 2.2.4 details the common models of sustainability obtained from these concepts. Section 2.2.5 discusses ways to measure progress towards sustainability using the common models of sustainability.

2.2.2 SUSTAINABILITY DEFINITIONS[†]

The long history of the sustainability concept has its beginnings in eighteenth century economic theory, which predicted a limit to economic growth caused by the availability of good agricultural land and scarcity of natural resources (Mebratu (1998)). More than a century later, in the 1960's and 1970's, the economist Ernest F. Schumacher introduced the idea that planners and policy makers should account for social welfare, resource depletion and environmental destruction when determining appropriate technology (Mebratu (1998)). However, it was not until the 1972 UN Conference on

[†] In keeping with traditional usage, sustainable development and sustainability are used interchangeably in this discussion.

Human Development in Stockholm that an international forum intimated that economic development may need to account for environmental concerns (Mebratu (1998)). At the same time, a group of eminent scientists and concerned citizens met in Rome ('The Club of Rome') and produced a comprehensive report, which emphasised that environmental emissions would soon exceed the limits of the earth to assimilate (Mebratu (1998)). During the next decade, UN reports steadily entwined the terms economic development and environment, until in 1980 a report used the term 'Sustainable Development' in its subtitle (Mebratu (1998)). Nevertheless, widespread discussion of sustainability was limited until the publishing of the UN-sponsored Brundtland report, WCED 1987 (Mebratu (1998)). Its most commonly quoted passage, which appears at the start of this chapter[‡], has spawned many interpretations of sustainability. There were more than 80 such interpretations in 1994, according to Holmberg (1994)[§] (Mebratu (1998)). After the Brundtland report, a number of world conferences highlighted sustainability, including the UN Conference on Environment and Development (UNCED)[**] in 1992, and the World Summit on Sustainable Development (WSSD) in 2002. Despite this long history, a definitive definition of the concept of sustainability is still lacking.

The definitions presented in the next few paragraphs were important in the formation of the author's views on sustainability. The definitions drawn from the Brundtland report usually emphasise needs, limits on development, inter-generational equity and intra-generational equity (Briassoulis (2001)[††]). They are concerned with the adverse effect that currently accepted methods of development have on the environment and social welfare (Pezzoli (1997)). One such interpretation, using the Brundtland report definition, and its further refinements, as its basis, consists of (Overcash (2001)):

- Direction of investments;
- Exploitation of resources;
- Orientation of technological development; and

[‡] The 'Brundtland definition', in the literature, usually refers to the statement 'To meet the needs of the present without compromising the ability of future generations to meet their own needs' (WCED (1987)).

[§] Mebratu (1998) does not provide details of this source.

[**] 'Rio Conference' and 'Earth Summit' are other commonly used terms for UNCED.

[††] This paper is a review, and thus other works are the source of this and many other statements.

- Institutional change.

The first point, 'Direction of investments', advocates the distribution of investment into areas to enable the fulfilment of the essential needs, e.g. jobs, food, energy, water and sanitation (i.e. social and economic growth) (WCED (1987)). Expressed in this point, is the Brundtland report's desire for intra-generational equity (worldwide equality) through directing funds into third-world (or developing) countries to eliminate absolute poverty (WCED (1987)). The second point, 'Exploitation of resources', advocates reducing industrial material and energy consumption, while distributing equitably the generated wealth (WCED (1987)). The third point, 'Orientation of technological development', advocates design of new technology to reduce environment impacts of the old, while ensuring that this new technology is chosen over less favourable options, if economic costs are similar (WCED (1987)). The last point, 'Institutional change', suggests the modification of government and legal frameworks to enforce the implementation of the first three points (WCED (1987)).

Another similar definition is that sustainability is 'a pattern of social and structural economic transformations (i.e. 'development') which optimises the economic and other societal benefits in the future' (Goodland and Ledec (1986)). This definition suggests that a sustainable economic activity is one in which social welfare is increased, while resource conservation is maximised, and environmental degradation is minimised, within given societal, economic and technical constraints (Barbier (1987)). Thus, human activity, i.e. development, which always involves both the consumption of resources and the emission of wastes, requires a 'pattern of activity...that is more resource- and waste-minimising than maximising' (Barbier (1987)).

Another definition, describes sustainability using 'sustainable livelihoods', which refers to 'a level of wealth and of stocks and flows of food and cash which provide for physical and social well-being and security against becoming poorer' (Chambers (1986)[‡‡]). This definition advocates a rise in real income for all, and increased stability of that income. This applies in rural society, for example, where natural events, such as droughts and floods, and the results of bad practices, i.e. salinity from over irrigation, can drastically affect income (Barbier (1987)). The global poor, in both urban and rural settings, are highly sensitive to these and other similar stresses (Barbier (1987)).

The previous three definitions applied a social perspective; others have applied

[‡‡] Excerpt from a discussion on this method in Barbier (1987).

economic theory. One such definition, defines sustainability as a dynamic equilibrium state lying between demand and supply (Figure 2.2.1) (Briassoulis (2001)). The society demands a desired development pattern for itself, in which the products must fit. Thus, suppliers of products that fail to meet the new pattern, modify their products and/or the technologies that produce them, to meet the new constraints.

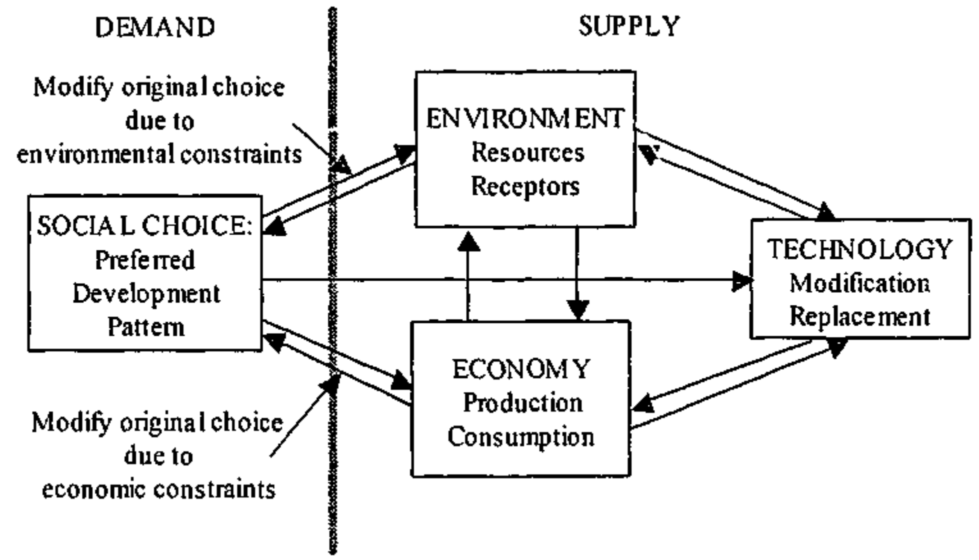

Figure 2.2.1: A representation of sustainability as a balance between economic supply and demand (modified from Briassoulis (2001).

2.2.3 Reasons for the Multiplicity of Sustainability Definitions

Most definitions have sought broad acceptability, rather than a precise, consistently interpretable and useable definition (Ayres (1996), Barbier (1987), Upham (2000)[§§]). Yet, no consensus as to the appropriate definition of sustainability exists (Ayres (1996), Azapagic and Perdan (2000), Briassoulis (2001), Cowell *et al.* (1999), Overcash (2001), Pezzoli (1997)[***]). Why is this so?

The word 'sustainable' has many meanings, such as 'keep into being', 'to provide with food and drink, or the necessities of life', and 'to endure without giving way or yielding', which are relevant in different ways to different groups: governments and organisations, the impoverished, and farmers and small business owners (Pezzoli (1997)). Thus, differences between the morality of the proponents of the definitions,

[§§] For example, The Natural Step Theory excludes limits of concentration and damage thresholds as they may introduce the 'potential for disagreement' (Upham (2000)).

[***] The authors of most other publications encountered also hold this opinion.

and the society that nurtured them (Buhrs and Aplin (1999)), generate different views on sustainability. Moreover, the views of the proponents are likely to change as their society changes (Briassoulis (2001)). Sustainability has been described in the literature as an 'amorphous concept', unable to be clearly defined (Overcash (2001)), and 'understood intuitively by all but very difficult to express in concrete, operational terms' (Briassoulis (2001)).

Some 'radical environmentalists' view this lack of definition as allowing for 'perverse' interpretations of the sustainability term, to allow 'business-as-usual (activities) or shallow rhetoric to win votes or placate customers or shareholders' (Ayres (1996), Buhrs and Aplin (1999)). Furthermore, some claim that it hinders application of the concept, leading to frustration and devaluing of the concept (Mebratu (1998)[†††]. Conversely, some view this lack of definition as ensuring continued effort. As the definition can evolve over time, the 'solving' of one problem will lead to a changed definition of sustainability (Wallace (1995)). This new definition may highlight some other problems for solving, rather than reduce the importance of the sustainability concept or encouraging its neglect (Wallace (1995)[‡‡‡]).

Consequently, it is likely that sustainability will remain a concept, grouping a number of definitions with similar ideals, rather than having a precise definition (Buhrs and Aplin (1999), Cowell *et al.* (1999)). Thus, described in the next section are models of the concept of sustainability, which rely less on a fixed model.

2.2.4 SUSTAINABILITY CONCEPT MODELS

Sustainability concept models include a number of definitions with similar ideals to formulate simple models of sustainability. The first such model separates sustainable development in three spheres: the economy, the environment and social welfare. Many proponents suggest three spheres as sufficient to define sustainability (Azapagic and Perdan (2000), Global Reporting Initiative (2002), Overcash (2001)). This concept is generally visualised using an intersecting goals diagram (see Figure 2.2.2), first used by Barbier (1987). The environmental system provides the raw materials for the economic system, and accepts wastes from both the economic and social systems (Azapagic and

[†††] Comments attributed to various sources: for more details see Mebratu (1998), pg. 503.

[‡‡‡] Statement obtained from its reproduction in Anderson (2001).

Perdan (2000)). The economic system provides goods and services to the social system (Azapagic and Perdan (2000)). Traditional development optimises economics alone, while Marxist economics optimises both social and economic system goals (Barbier (1987)). Traditional environmental analysis optimises environmental goals or a combination of environmental and economic goals. Sustainability optimises each of the three system goals.

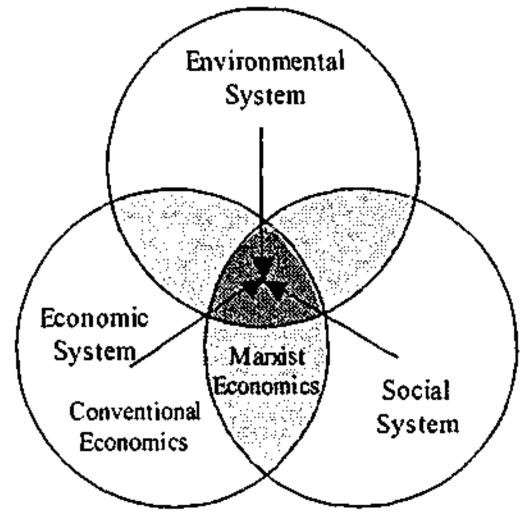

Figure 2.2.2: Three-sphere representation of the concept of sustainability (adapted from Barbier (1987)). The arrows represent optimisation towards sustainability.

While the three intersecting spheres model was prevalent in the literature, other models exist. Once such model shows four intersecting spheres ('political ecology'): a. the environment (and history and power); b. the legal-institutional terrain; c. culture and civil society; and d. the economy and technology (Figure 2.2.3) (Pezzoli (1997)). This model disaggregates the social sphere of the three-sphere model into two spheres: b. and c. This four sphere model is perhaps better at defining sustainability, than the three-sphere model, as there are differences between how institutions (sphere b.) and its people (sphere c.) would need to act and how they would be effected by a movement towards sustainability. The UN's Division for Sustainable Development also uses a four-sphere model: social, economic, environmental and institutional (Division for Sustainable Development (2003)).

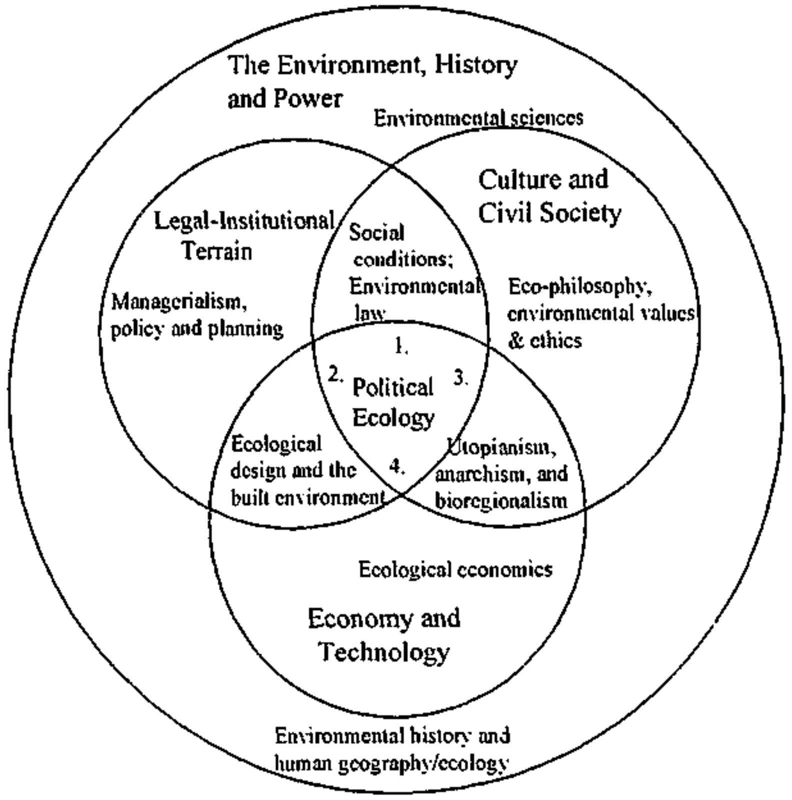

Figure 2.2.3: Four-sphere representation of the concept of sustainability (Pezzoli (1997)). Marked are corresponding branches of economic and political literature. The numbers represent: 1 Holism; 2 Empowerment and community building; 3 Social justice and equity; and 4 Sustainable production and reproduction.

2.2.5 Reaching Sustainability

The interaction of the spheres in the three sphere concept model is complex. With increased development of the concept of sustainability, has come an improved understanding of the interrelations of its spheres (Board on Sustainable Development (1999)). Empirical evidence for the interdependence of the three spheres was provided through a study that showed that US states with lower pollution levels and greater environmental controls had stronger economies and reduced income disparity (mentioned in Guy and Kibert (1998)[§§§]). The optimisation of one impact is unlikely to give the optimum result for all impacts (Barbier (1987), Overcash (2001)). Consequently, ensuring maximum sustainability benefit may require trade-offs between the spheres (Barbier (1987), Overcash (2001)). For example, sacrifice of some measure of financial benefit may result in a more socially attractive employment strategy rather

[§§§] Study mentioned: Templet, P.H. (1995), *The positive relationship between jobs, environment and the economy: an empirical analysis and review*, Spectrum, Spring, 37.

than a fully mechanised alternative[****]. There is some disagreement about the substitutability of items within different spheres (Ayres (1996)): such as how many jobs (man-made capital) are equivalent to a tree (natural capital). Some economists would allow substitution of such items on a cost basis, while others declare many such items unsubstitutable (Ayres (1996)). Trade-off would require some way of quantifying the contribution of each to sustainability by adjudging the relative importance of that measurement. None of the definitions of the sustainability concept allowed quantification of sustainability, as they sought broad acceptance, rather than sharp definition (Ayres (1996), Bell and Morse (2001)). Others have suggested that it is possible to produce such a definition (Matson and Carasso (1999)). Therefore, to use the three-sphere concept model an alternative method of quantification is necessary.

2.2.6 Summary of Defining Sustainability

Sustainability and sustainable development are commonly used terms, in industrial, governmental and other reports, when describing actions taken (Cowell *et al.* (1999), Pezzoli (1997)). Yet, there remains no consensus on their definition. Therefore, practitioners have developed concept models, which consider only areas of broad agreement, to allow further work in sustainability assessment. The concept model most prevalent has three spheres representing the economy, environment, and society. The use of these concept models requires the ability to quantify the contributions to each sphere, which none of the definitions of sustainability allow. Consequently, alternative methods for measuring sustainability are necessary.

2.3 *MEASURING SUSTAINABILITY*

2.3.1 Overview of Measuring Sustainability

Key to the practical use of the sustainability concept is the ability to quantify sustainability. This will require the development of analytical tools (Barbier (1987)), as has been achieved in other forms of assessment. Different definitions require often

[****] See Barbier (1987) and Overcash (2001) for further examples.

entirely different measures, e.g. quality of life (social measure) and resource scarcity (material measure). Thus, the tools developed from definitions will necessarily vary. This section reviews some of the proposed tools for measuring sustainability and assesses their suitability for sustainability assessment using the three-sphere concept model (see Section 2.2.4).

Section 2.3.2 presents this review, and selects an appropriate method. Section 2.3.3 then examines the selected method in greater detail. Section 2.3.4 discusses the application of the selected method for industrial systems. Often assessment methods use criteria to adjudge progress towards their goal. Section 2.3.5 discusses the use of criteria in sustainability assessment. Another important choice in assessments is that of boundary placement. Section 2.3.6 discusses appropriate boundaries for sustainability assessments.

2.3.2 TOOLS FOR MEASURING SUSTAINABILITY

Despite the wide range of tools for sustainability they share a number of common themes. For example, many tools share common tasks, such as to (from Barbier (1987), Briassoulis (2001) and Overcash (2001)):

a. evaluate existing sustainability performance and indicate problem areas;

b. monitor progress towards, or away from, enhanced sustainability;

c. compare alternative designs for both improvements and new systems;

d. estimate the effectiveness of the improvements to sustainability performance;

e. ensure application of identified improvements; and

f. identify unintended consequences of improvements.

A sustainability tool must be able to determine the degree of optimisation of each sphere of sustainability (Overcash (2001)), i.e. environment, economy and social welfare, and estimate the effect on this optimisation of possible trade-offs between the aspects. As the sustainability concept includes many different types of effects, tool development should utilise people from various backgrounds and disciplines, such as science, engineering, social science, and economics (Hammond (2000)). Most importantly, for the tool to obtain wide acceptance it must have scientific and social credence and be both practical and effective (Board on Sustainable Development

(1999)).

Early workers suggested a combined single indicator for sustainability, expressed as an index (i.e. 'basic needs' or 'physical quality of life') (Barbier (1987)). In the building industry these and other indicators (i.e. sustainable community, healthy community, human development, and urban environment) have been proposed and developed in an 'attempt to create the most balanced approach' to the three spheres (Guy and Kibert (1998)). Developing these types of aggregated indicators requires the use of techniques such as brainstorming, focus groups, expert opinion, surveys and other quantitative and qualitative measurements (Guy and Kibert (1998)). They are designed to provide a basic test, for the local community, which hints at the 'big picture' of the sustainability of the development, through the measurement of simple, discreet sources of information (Guy and Kibert (1998)).

One such method, the Sustainable Process Index, attempted to estimate the required surface area of earth required to negate the detrimental effects of the process on sustainability. However, its coverage was limited, considering only environmental impacts and employment (Krotscheck (2000)). The World Wide Fund for Nature was reporting an environmental version of this, the Eco-footprint, in 1992 (World Wide Fund for Nature (2002)). Another, widely promoted example, Eco-Efficiency, was developed by 'business for business' by the World Business Council for Sustainable Development, which includes both environmental and economic measures in its indicator, covering seven impacts: material intensity; energy intensity; toxic dispersion; recyclability; non-renewable resource consumption; product durability; and product service intensity (Azapagic and Perdan (2000), de Simone and Popoff (1997)). Many other combined indicators exist, some for use in industrial systems[††††]. Some of these were for internal use by specific companies (i.e. ICI and Unilever), and others by industrial or governmental organisations (i.e. AIChE, UNEP, the World Resources Institute, etc.) for wider application. Most of these included mainly environmental factors (Azapagic and Perdan (2000)).

Other tools convert social and environmental impacts into economic impacts (IAEA (2000)). For example, Virtual Eco-Costs '99 proposed the use of the ratio of the last and most expensive cost associated with negating an environmental effect, to the sum of the product's economic costs, taxes, and profits (Vogtländer *et al.* (2001)), as an

[††††] See Azapagic and Perdan (2000) for a more detailed review of these indicators.

appropriate method for weighting impacts. Dispute continues about the validity of placing economic values on environmental and social impacts (Verbuggen and Kuik (1991)). For example, the valuation of impacts such as illness, human life, and visual intrusion (among others) present difficulties (IAEA (2000)).

The integration procedure is often an area of dispute, as it is not possible, using current methodologies, to provide a scientific weighting system free of value choices (Briassoulis (2001)). This is due mainly to the morality, cultural, and other differences between societies (see Section 2.2.2). For example, while water and air pollution were considered high priority hazards in most nations, industrialised nations also ranked ozone depletion and climate change highly, while less industrialised nations ranked drought or flood, disease, and the availability of living resources in their place (Board on Sustainable Development (1999)). Consequently, a combined measure of sustainability would be pertinent only for those who concur with the values used in its weighting mechanism. Sustainability is too complex to allow its measurement with a single measure, and thus sets of measures (or indicators) are more common (Bell and Morse (2001), Board on Sustainable Development (1999), Briassoulis (2001), Verbuggen and Kuik (1991)).

2.3.3 Indicators for Measuring Sustainability

Indicators have a long history of widespread use and acceptance in measuring effects in all type of assessments (Bell and Morse (2000), Board on Sustainable Development (1999), Pezzoli (1997)). Indicators are useful for communication with society and governments, and may point out impediments to sustainable development in the community (Guy and Kibert (1998)). Indicators generally give measures of the existing degree of sustainability (compared to a reference), an indication of the difference between modification (or new) options, or monitor the effects of previous changes (Ayres (1996), Briassoulis (2001)).

They should ideally (Bell and Morse (2001), Braiassoulis (2001), UNCED (1992)):

1. be comprehensive in their coverage of the social, economic and environmental impacts;
2. integrate impacts using an accurate, reliable and comprehensive method;
3. consider effects at all time scales; and
4. be developed with stakeholders (i.e. the affected members of the community)

and those who will use them.

They should be able to (Beli and Morse (2001), Guy and Kibert (1998)):

A. provide valid, reliable, and relevant results;
B. only require measurable information[‡‡‡‡];
C. be responsive and adaptive to changes in the indicated system and the community; and
D. be understandable to all.

This desire for understandability should not detract from complete guidance on how to measure the indicators, as has often occurred (Bell and Morse (2001), Veleva and Ellenbecker (2001)).

Most environmental indicators had their birth in the 1980's (Briassoulis (2001)), when many environmental methodologies and sustainability were initially developed. Social impacts are 'emotive and normative issues' and cannot easily be considered in simple indicators or then objectively compared to other impacts (Bell and Morse (2001)). Thus, no standard way for determining social performance exists, and social indicators are less well defined (Azapagic and Perdan (2000)). Thus, indicators tend to (Azapagic and Perdan (2000), Briassoulis (2001), Guy and Kibert (1998), Veleva and Ellenbecker (2001)):

i. measure environmental and economic features well;
ii. consider social impacts poorly (if at all);
iii. be aggregates of individual indicators rather than all embracing measures of the desired impact;
iv. be indicators of local impacts rather than national or global;
v. use only quantitative measures, excluding immeasurable impacts;
vi. be still under development;
vii. be chosen from a list of indicators for each individual application;
viii. lack detailed guidance on application; and
ix. be used by internal management, rather than for external reporting.

Some have suggested that the use of these existing indicators has little benefit, as they contain little human value content, while measuring something that is 'highly subjective and ridden with human values and desires' (Bell and Morse (2001), Briassoulis (2001)).

There are a great number of sets of indicators of sustainability (Bell and Morse (2001), Board on Sustainable Development (1999)). Some examples of bodies producing indicator sets include: the United Nations (Division for Sustainable Development (2003)); national (i.e. DETR (U.K.) (2001)) and local governments (see International Sustainability Indicators Network (2003) for examples); professional bodies and industry organisations (i.e. IChemE (2002a)); and academic-industry collaborations (i.e. Global Reporting Initiative (2002)). The United Nations indicator set (shown in Table 2.3.1 to Table 2.3.4), based on the four-sphere model, is an example of an indicator set suited to the assessment of a nation's sustainability. In OECD countries, the data required for these indicators was available (Ayres (1996)). Some countries, notably the U.K., publish a number (120) of sustainability indicators (DETR (U.K.) (2001)).

Indicators must be relevant to the policy options under consideration for them to be of value to the decision maker (Cardwell *et al.* (1995), International Institute for Sustainable Development (2000), Verbuggen and Kuik (1991)). Thus, while there are many indicators available, not all will be relevant in each situation. The chosen indicators cannot be too few, for this may exclude important impacts. Therefore, the choice of an appropriate set of indicators is an important decision, which will dictate the accuracy and defensibility of the sustainability assessment. A scientific basis for the selection of the appropriate indicators for each situation is lacking (Board on Sustainable Development (1999), International Institute for Sustainable Development (2000)). One attempt[§§§§] at providing such a basis suggested (International Institute for Sustainable Development (2000)):

**** This may include non-technical measures, such as survey results.

§§§§ The authors acknowledge that this set is incomplete.

Table 2.3.1: The United Nations proposed national indicators for the social sphere of sustainability (Division for Sustainable Development (2003)).

Theme	Sub-theme	Indicator
Equity	Poverty	Percent of Population Living below Poverty Line
		Gini Index of Income Inequality
		Unemployment Rate
	Gender Equality	Ratio of Average Female Wage to Male Wage
Health	Nutritional Status	Nutritional Status of Children
	Mortality	Mortality Rate Under 5 Years Old
		Life Expectancy at Birth
	Sanitation	Percent of Population with Adequate Sewage Disposal Facilities
	Drinking Water	Population with Access to Safe Drinking Water
	Healthcare Delivery	Percent of Population with Access to Primary Health Care Facilities
		Immunization Against Infectious Childhood Diseases
		Contraceptive Prevalence Rate
Education	Education Level	Children Reaching Grade 5 of Primary Education
		Adult Secondary Education Achievement Level
	Literacy	Adult Literacy Rate
Housing	Living Conditions	Floor Area per Person
Security	Crime	Number of Recorded Crimes per 100,000 Population
Population	Population Change	Population Growth Rate
		Population of Urban Formal and Informal Settlements

a. Policy relevance (can policies be formulated from it);
b. Simplicity;
c. Validity (does it measure a sustainability impact accurately, defensibly, verifiably and reproducibly);
d. Time-series data (can the variance with time be followed);
e. Data availability (can the data be affordably obtained);
f. Scope (does it aggregate several more narrow indicators without losing information);
g. Sensitivity (can it detect small changes); and
h. Reliability (can the same result be obtained by other workers).

2.3.4 INDICATORS FOR INDUSTRY

Companies, influenced by public concern, regulatory pressures and other factors, have

Table 2.3.2: The United Nations proposed national indicators for the environmental sphere of sustainability (Division for Sustainable Development (2003)).

Theme	Sub-theme	Indicator
Atmosphere	Climate Change	Emissions of greenhouse gases
	Ozone Layer Depletion	Emissions of ozone depleting substances
	Air Quality	Ambient concentration of air pollutants in urban areas
Land	Agriculture	Arable and permanent crop land area
		Use of fertilizers
		Use of agricultural pesticides
	Forests	Forest area as a percent of land area
		Wood harvesting intensity
	Desertification	Land affected by desertification
	Urbanization	Area of urban formal and informal settlements
Oceans, Seas and Coasts	Coastal Zone	Algae concentration in coastal waters
		Percent of total population living in coastal areas
	Fisheries	Annual catch by major species
Fresh Water	Water Quantity	Annual withdrawal of ground and surface water as a percent of total available water
	Water Quality	BOD in water bodies
		Concentration of faecal Coliform in freshwater
Biodiversity	Ecosystem	Area of selected key ecosystems
		Protected area as a percentage of total area
	Species	Abundance of selected key species

become interested in sustainability assessment. Companies desired broadly accepted measures of sustainability to enable both audits of sustainability status and alignment with the sustainability goals of its partners and regulators (Global Reporting Initiative (2002)). Institutions and regulatory authorities, driven by the expectations of international bodies and their own population, also desire companies to measure sustainability (Global Reporting Initiative (2002), Buhrs and Aplin (1999)). Moreover, financial markets are beginning to desire such information, due to demands for socially and ethically responsible investments (Global Reporting Initiative (2002)). Thus, many companies have developed their own indicators.

Many of the impacts on sustainability, measured by indicators for nations, are inconsequential to the operation of a single company or industry. For example (from Table 2.3.1) crime rates, healthcare delivery, and many others. Thus, different indicator sets are necessary. Figure 2.3.1 shows a suggested scheme for organisations to develop their own indicator sets. In this scheme, companies begin with simple, easily

Table 2.3.3: The United Nations proposed national indicators for the economic sphere of sustainability (Division for Sustainable Development (2003)).

Theme	Sub-theme	Indicator
Economic Structure	Economic Performance	GDP per capita
		Ratio of capital investment to GDP
	Trade	Balance of trade in goods and services
	Financial Status	Debt to GNP Ratio
		Total official development assistance given or received as a percent of GNP
Consumption and Production Patterns	Material Consumption	Intensity of material use (mass or volume per GDP)
	Energy Use	Annual energy consumption per capita
		Share of consumption of renewable energy resources
		Intensity of energy use
	Waste Generation and Management	Generation of industrial and municipal solid waste
		Generation of hazardous waste
		Management of radioactive waste
		Waste recycling and reuse
	Transportation	Distance travelled per capita by mode of transport

Table 2.3.4: The United Nations proposed national sustainability performance indicators for the institutional sphere of sustainability (Division for Sustainable Development (2003)).

Theme	Sub-theme	Indicator
Institutional Framework	Strategic Implementation of SD	National sustainable development strategy
	International Cooperation	Implementation of ratified global agreements
	Information Access	Number of internet subscribers per 1000 inhabitants
	Communication Infrastructure	Main telephone lines per 1000 inhabitants
Institutional Capacity	Science and Technology	Expenditure on research and development as a percent of GDP
	Disaster Preparedness and Response	Economic and human loss due to natural disasters

implemented compliance indicators, before moving on to more complex indicators and life-cycle impacts (Veleva and Ellenbecker (2001)).

Industrial indicators have additional requirements to those of general indicators of sustainability. Industrial systems have many operating parameters that may be changed. Indicators must be measurable, at specific, sufficiently frequent time intervals, to show

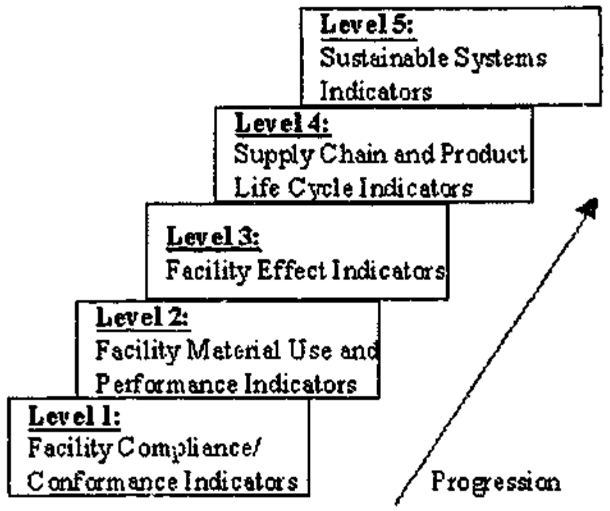

Figure 2.3.1: Framework for organisations to develop sustainability indicators (Veleva and Ellenbecker (2001)).

the variation in indicator values with changes in operating parameters (Briassoulis (2001)). A company or industry may have operations in many locations. Thus, the indicators must also have well defined, and explained, boundaries, indicating whether the measurement is specific to a particular processing area or facility, or to the entire product life cycle (Veleva and Ellenbecker (2001)).

It is unlikely that any one set of indicators could be applicable to all organisations, as each production facility would have its own key impacts (Veleva and Ellenbecker (2001)). Thus, development of an all-encompassing, sustainability indicator list is unlikely. Some have proposed a default set that practitioners either, choose relevant indicators from within it (Azapagic and Perdan (2000)), or add missing indicators to a basic set (Veleva and Ellenbecker (2001)). This may increase the likelihood of the standardisation of an indicator set and method for sustainability assessment (Azapagic and Perdan (2000)). Revision of the standardised group of indicators could occur periodically as the concept, scientific knowledge, technology (Briassoulis (2001)) and definition of sustainability evolve. A standard set of indicators has yet to be accepted (Azapagic and Perdan (2000), Board on Sustainable Development (1999)).

One attempt at a default set of indicators, by the Global Reporting Initiative (Global Reporting Initiative (2002)), developed a detailed scheme with the interaction of a number of academics and some large multinational corporations (e.g. BASF, Bayer, Gaz de France, Rio Tinto, Royal Dutch/Shell, Texaco, TotalFinaElf, Transalta, and TXU Europe). Another attempt, by Azapagic and Perdan (2000), was consequently

adopted (with some modification) by the Institution of Chemical Engineers (UK) (see IChemE (2002a)). Table 2.3.5 and Table 2.3.6 show these two indicators sets.

Despite the development of a great number of indicators and frameworks, there are only a very few published examples of their use in decision-making (by those for whom they are developed) (Bell and Morse (2001)). This may be due to their development by external experts, or executive management (Bell and Morse (2001)). This may orientate them towards symbolic use (publicity), rather than the envisioned practical application (Buhrs and Aplin (1999)). Moreover, evidence has revealed, that many companies fail to locate and reduce the major environmental and social impacts, because standardised methods and measures for these impacts are lacking (Veleva and Ellenbecker (2001))[*****]. Thus, the borrowing of an existing method for use in this assessment of the sustainability of electricity generation systems, for instance, is not feasible.

2.3.5 Criteria for Sustainability and Sustainability Indicators

Each of the spheres of the sustainability concept models has their own goals, which are 'human-ascribed' (Barbier (1987)), and thus, are value, rather than scientifically based. Table 2.3.7 provides examples of the system goals espoused by Barbier (1987) for his definition of sustainability (see Section 2.2.2). The Brundtland report contains similar goals (WCED (1987)). The goals ascribed, will depend on the relative importance that individuals place on each of the three spheres (Overcash (2001)). It is likely then that these goals will vary as perceptions of what is necessary for sustainability change (Board on Sustainable Development (1999)).

Criteria are goals (targets) for achievement, which are less than the ultimate goal, but represent a short-term goal or requirement. Criteria will usually refer to the reduction or increase of an indicator magnitude over a fixed time. For example, the Kyoto protocol, which required signatories to meet 'greenhouse gas' emissions targets by 2010, is a sustainability criterion for the 'Global Warming' indicator. Criteria may be set internally, by regulators, or social groups (Briassoulis (2001)). Constraints on the setting of appropriate criteria, especially for natural resources, are (Briassoulis (2001),

[*****] As reported in a review of company sustainability reports (SustainAbility (2000), *Team Spotlights Top 50 Corporate Sustainability Reports*, GreenBiz, http://www.greenbiz.com/news/newsFthird.cfm?NewsID=13397).

Table 2.3.5: Proposed default set of indicators for assessing the sustainability of organisations (Global Reporting Initiative (2002)).

Sphere	Category	Aspect
Economic	Direct Economic Impacts	Customers
		Suppliers
		Employees
		Providers of capital
		Public sector
Environmental	Environmental	Materials
		Energy
		Water
		Biodiversity
		Emissions, effluents, and waste
		Suppliers
		Products and services
		Compliance
		Transport
		Overall
Social	Labour Practices and Decent Work	Employment
		Labour/management relations
		Health and safety
		Training and education
		Diversity and opportunity
	Human Rights	Strategy and management
		Non-discrimination
		Freedom of association and collective bargaining
		Child labour
		Forced and compulsory labour
		Disciplinary practices
		Security practices
		Indigenous rights
	Society	Community
		Bribery and corruption
		Political contributions
		Competition and pricing
	Product Responsibility	Customer health and safety
		Products and services
		Advertising
		Respect for privacy

(George (2001)):

1. Scientific uncertainty;
2. Limited information;
3. Unknown effects from interactions between the system and its surroundings;

Table 2.3.6: Proposed default set of indicators for assessing the sustainability of organisations (Azapagic and Perdan (2000)).

Environmental	Economic	Social
Environmental Impacts	**Financial Indicators**	**Ethics Indicators**
Resource use	Value added	Preservation of cultural values -stakeholder inclusion -involvement in community projects
Global Warming	Contribution to GDP	
Ozone Depletion	Expenditure on environmental protection	
Acidification		
Eutrophication	Environmental liabilities	International standards of conduct -business dealings -child labour -fair prices -collaboration with corrupt regimes
Photochemical Smog	Ethical investments	
Human toxicity	**Human-capital indicators**	
Eco-toxicity	Employment contribution	
Solid Waste	Staff turnover	
Environmental efficiency	Expenditure on health and safety	
Material and energy intensity		
Material recyclability	Investment in staff development	Intergenerational equity
Product durability		**Welfare indicators**
Service intensity		Income distribution
Voluntary actions		Work satisfaction
Environmental management systems		Satisfaction of social needs
Environmental improvements above the compliance levels		
Assessment of suppliers		

Table 2.3.7: Proposed goals of sustainability (goals presented for each sphere of the three-sphere sustainability model) (Barbier (1987)).

Environmental	Economic	Social
Genetic diversity	Satisfying basic needs	Cultural diversity
Resilience	Equity-enhancing	Institutional sustainability
Biological productivity	Increasing useful goods and services	Social justice
		Participation

4. Value choices in weighting of impacts and qualitative indicators;
5. The continual redefinition of sustainability goals;
6. The clear specification of spatial boundaries and temporal horizons; and
7. The interdependence of individual targets on the attaining of others.

Analysis of these constraints was uncommon in the development of existing international conventions and agreements for criteria (Board on Sustainable Development (1999)).

Some have suggested that the specification of criteria is necessary for progress to occur, especially as institutions (Ekins and Simon (2001)) and organisations preferably work towards targets. However, each practitioner may suggest different possible criteria for the indicators, as each may consider different impacts on sustainability to be most important (Ekins and Simon (2001)). For example, if one practitioner considers human health most important, then emissions of substances which have worst human health effects is paramount. Thus, this practitioner's criterion might be the reduction or elimination of these emissions. If another practitioner believes a different impact to be most important, then their chosen criteria will reflect this belief, and is unlikely to be the same as the criterion based on human health. Thus, the setting of criteria leads not to greater sustainability, but argument over the validity of the target.

Other alternative methods of judging improvement in sustainability include the multi-criteria (or multi-objective) technique, which optimises all indicators simultaneously to select the lowest impact solution (IAEA (2000)). However, the method requires the setting of criteria. Alternatively, a plot of two or three key impacts may show the optimum choice (see Figure 2.3.2). This method enables the selection of a reasonable compromise, even if there is no 'best' option (IAEA (2000)). Golonka and Brennan (1997) discuss some trade-off and other alternative methods for use with environmental and economic impact aggregates.

Without criteria, the multiplicity of views on sustainability may be more easily integrated, and approaches and tools may then adapt to particular views as necessary (Briassoulis (2001), McQuaid (2000)). Thus, discussion has shifted from determining criteria, to considering progress towards the final goal: sustainability (Briassoulis (2001), George (2001)). For example, a modification that leads to a general improvement in sustainability indicators enhances sustainability.

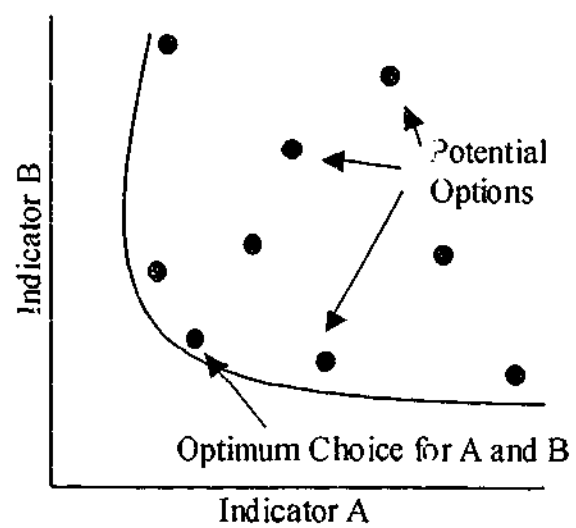

Figure 2.3.2: An example of a plot to examine options for trade-off of notional indicators A and B.

2.3.6 Boundaries for Measurement of Sustainability

Well-defined spatial and temporal boundaries are additional requirements for industrial indicators over regional indicators (see Section 2.3.3). The spatial boundary of a sustainability assessment should ideally be a naturally bounded area, such as a watershed, or an economically bounded area, such as a nation (Briassoulis (2001)), depending on which paradigm is more central to the definition used. Regional areas are suggested as the most appropriate level as they are most likely to have their environmental, economic and social processes integrated (Briassoulis (2001)). By increasing the size of the boundary, it becomes more likely that all impacts on sustainability will be included, but the complexity increases and the study may become unworkable (Briassoulis (2001)). Conversely, a smaller region may have many influences external to the region, and hence out of direct control (Briassoulis (2001)). Indicator sets using a regional boundary are most effective if developed at a local level (i.e. 'Local Agenda 21'), where a more comprehensive coverage of viewpoints is possible (UNCED (1992)). Thus, the resulting indicator would be specific to the local community and have limited applicability on larger scales.

In an organisation, likely spatial dimensions for a study include single facilities, groups of facilities in a similar region or producing similar products (a sector), or a company as a whole. Such a study would most likely following existing business divisional lines. As with indicator sets using regional boundaries, the indicator sets developed for an organisational boundary are likely to be specific to the organisation, and thus have limited applicability on larger scales.

An alternative to these boundary types is the 'life-cycle' perspective. The 'life cycle' perspective boundary follows the life of a product, from raw materials in nature, through successive processing stages, use, and ultimately to disposal. By choosing the life cycle perspective, comparisons both within sectors and between sectors are possible, and the shifting of poor sustainability operations to other locations, beyond the considered administrative boundary[†††††], can be minimised (Ayres (1996)). This 'life

[†††††] For example, consider a product, which has many processing stages, two of which (A and B) occur at a single location. Stage B is 'unsustainable' in its operation, in comparison to stage A. If the boundary is around the fixed site, then moving stage B to another location (outside the boundary) will improve the 'level of sustainability'. However, for a 'life cycle' boundary, the moving of stage B would not enhance the 'level of sustainability'.

cycle' perspective is of increasing interest in environmental analysis, and sustainability (Ayres (1996), Azapagic and Perdan (2000), Board on Sustainable Development (1999), Cowell *et al.* (1999)). The United Nations suggested it was essential for the sound management of chemicals and hazardous wastes (United Nations (2002)). Others have made similar claims for design and engineering (Heaney (1995)[‡‡‡‡‡]), and sustainability assessment (Azapagic and Perdan (2000)).

2.3.7 Summary of Measuring Sustainability

Each of the sustainability tools discussed conceivably is applicable to assessments of electricity generation systems. The methods that utilise sets of indicators have important advantages over the alternatives, including the flexibility to be relevant to a wide range of systems and societies and widespread acceptability. Highlighted are some indicator sets for use in industrial situations, but their application is not simple. Indicators of sustainability must be relevant to the needs of the assessment. Thus, to apply the existing indicator sets to electricity generation systems, modifications will be necessary to select the appropriate indicators of sustainability.

2.4 *ELECTRICITY GENERATION AND SUSTAINABILITY*

2.4.1 Overview of Electricity Generation and Sustainability

An important observation of Section 2.3 was that knowledge of the sustainability impacts important to the study subject is necessary to measure sustainability using indicators. Many studies into economic, environmental, or social performance of electricity generation and supply have covered some impacts of sustainability. Each considers different systems and ranges of impacts. Some, for example, include only the economic impacts of an electricity generation plant. Others apply the 'life-cycle' perspective, but include only specific environmental effects, such as climate change. A

‡‡‡‡‡ From Hatch, H. J. (1994), *Accepting the Challenge of Sustainable Development*, in American Association of Engineering Societies (AAES), *The Role of Engineering in Sustainable Development*, AAES, Washington D.C. (U.S.A.).

review of these studies provides a perspective of the most important impacts to electricity generation. Sustainability indicators to represent these impacts can then be selected from Section 2.3. Therefore, this section establishes which sustainability impacts are of most importance for the study of electricity generation using fossil fuels.

Section 2.4.2 discusses the necessity for a sustainability assessment of electricity generation from fossil fuels. Section 2.4.3 contains a review of studies on electricity generation. Section 2.4.4 reports the most important sustainability impacts and the sustainability indicators, which can represent them. It also examines the reasoning for the selection and rejection of suitable sustainability indicators.

2.4.2 Electricity and Sustainability

Chapter 1 expressed a number of important links between electricity generation and sustainability. This section expands on those links, and provides a number of views on strategies to limit the effects of electricity generation on sustainability.

Planning for electricity generation and provision has been *ad hoc*, to meet the short-term goals of institutions and organisations (WCED (1987)). Yet, energy development is too important for survival to continue in this manner (WCED (1987)). The primary objective of traditional electricity system development was to produce the required electricity at the lowest cost (IAEA (2000)). Immediate needs were paramount, including customer service, risk, financial and technological flexibility, and competition (IAEA (2000)). These policies use energy market prices or forecasts of energy supply limitations for their decision-making tools (Anderson (2001), IAEA (2000)). Variances in the availability and price of fuels often lead to profound changes in energy source usage (Hammond (2000)). For example, coal fuelled the economic recovery of Europe in the 1950's, but its high price soon led to its replacement with cheaper oil fuels (Hammond (2000)). Thus, primarily the bases for choices between options were economic, such as highest net present value or ranking from a cost/benefit analysis (IAEA (2000), Matson and Carasso (1999)). These methodologies would thus exclude any costs (and benefits) which cannot be expressed in monetary terms, and will discount those, which can be so expressed, but occur at times far removed from the initial investment (Matson and Carasso (1999)). Environmental costs did enter into earlier energy strategy decisions, but only in the costs of technology required to meet pollution standards (IAEA (2000), Matson and Carasso (1999)). Detailed environmental assessment, as a separate Environmental Impact Assessment (or Statement), aimed to show compliance with regulatory limitations (IAEA (2000)). Sustainable electricity production criteria should include both the traditional requirements of sufficient and reliable (i.e. diverse sources, and secure supply chain) supply, and protection of human health and the environment (IAEA (2000), Matson and Carasso (1999)). Thus, the basis for these planning methods is a system of values 'that are increasingly in conflict with a sustainable planetary future' (Matson and Carasso (1999)).

It has been concluded that no mix of current electricity generation can be sustainable (WCED (1987)). Further, there was no one perfect method or energy source for electricity generation (IChemE (2002b). All energy sources have their own, unique economic, environmental and social cost and benefits (WCED (1987)), or sustainability. Some examples are: resource scarcity; smog generated in cities from road traffic; acid rain; and climate change from greenhouse gas emissions (Hammond (2000)). Fossil fuel systems are ultimately unsustainable because the reserves of fossil fuels are exhaustible (Graedel (2002), International Energy Agency (2001), and many others).

Only renewable energy technologies appear to be sustainable (Hammond (2000), Matson and Carasso (1999), WCED (1987)), however they too cause impacts[§§§§§] (OECD (1985)). Moreover, some predictions of the extent of renewable energy technologies development claim minimal use, to 2020 (IAEA (2000), IEA (2001)), and even to 2050 (Hammond (2000)). Other predictions are less pessimistic (Board on Sustainable Development (1999), Graedel (2002)), one stating that transition to sustainability could occur by 2050, while the other claimed that up to 60 % of energy could be produced sustainably by 2050, and 100 % by 2100 (Graedel (2002)). The criterion for sustainability in these predictions was low 'greenhouse gas' emissions, and thus it includes (fissile) nuclear energy sources (Graedel (2002)). However, nuclear energy sources consume resources, and that resource was similarly restrictive (20-50 years), not allowing nuclear to substantially increase its share of world energy production without major advances in the efficiency of energy conversion (Nakĕ enovĕ *et al.* (1998))[******]. Nuclear technology is unlikely to be practical in Australia, despite

§§§§§ For example, wind generation has impacts such as noise, visual, material consumption in construction and maintenance, and bird destruction. Solar generation has impacts in land-use, and material consumption in construction and maintenance.

****** The successful development of fast breeder reactor technology could provide energy for up to 8000

the abundance of fuel (uranium), since public opinion in Australia is firmly against its use.

Optimistic predictions assume that the public support indicated for progress ensures political, social, and economic support for the utilisation of technological advances (Board on Sustainable Development (1999)). By contrast, some predictions are pessimistic because of the extant economic and institutional constraints on renewable technology growth (WCED (1987)). The economic constraints are due mainly to the higher capital costs of renewable energy schemes for the same output of electricity. Under the prevailing methods for determining electricity costs, capital expenditure has greater weight than the on-going fuel costs associated with non-renewable technologies (Anderson (2001), Matson and Carasso (1999)). Institutional constraints are those of government control of energy systems, where piecemeal decisions by the government of the day lead to large centralised conventional (non-renewable) energy schemes (Anderson (2001)). Yet, these same institutions must introduce measures to support the implementation of renewable energy technologies if they are to become prevalent (IEA (2001)).

Pessimistic predictions also point out that some renewable technologies, like wind and wave power, produce electricity at unpredictable levels (IChemE (2002b)). Fossil fuel technology is necessary to ensure stable electricity provision, when renewables supply greater than 10 % of the grid power (IChemE (2002b)). IChemE (2002b) claim that this necessity would reduce the possible environmental impact benefit from the use of renewable technologies rather than fossil fuels by 50 %. Furthermore, when such technologies produce no power at all (i.e. on calm days), they require back-up power generators, most likely fossil fuel technologies, which add to costs and environmental effects (IChemE (2002b)). Renewable energy systems will become more important with the development of large-scale electricity storage enabling the smoothing of high and low productivity conditions (Royal Dutch/Shell (2001)).

Cogeneration systems can produce electricity with much lower impacts than standard fossil fuel systems. However, they can find the challenge of competing on the electricity and heat markets difficult (Matthes and Timpe (2000)). The high cost of installation of district heating networks precludes the use of cogeneration over wide areas (IAEA (2000)). Therefore, cogeneration systems have greatest potential for steam

years (IAEA (2000), Nakĕ enovĕ *et al.* (1998)).

supply to industries, across plant boundaries. Yet, only a minority of present cogeneration systems share steam between multiple industries††††††, indicating that such arrangements are also difficult.

Consequently, renewable, cogeneration and nuclear technologies cannot provide a significant proportion of Australia's electricity production. Therefore, Electricity development strategies must increase the sustainability of the current system, while still using conventional fossil fuels. Advanced technology coal fuelled systems were recognised as an important technology for such schemes, due to the expected ability of such schemes to reduce environmental impacts, and expected increases in the cost of natural gas (IChemE (2002b), United Nations (2002)). Thus, it is necessary to establish the sustainability impacts of both conventional and advanced electricity generation technologies for fossil fuels.

2.4.3 STUDIES OF ELECTRICITY GENERATION

2.4.3.1 OVERVIEW OF STUDIES OF ELECTRICITY GENERATION

This review of studies of electricity generation includes sustainability (Section 2.4.3.2), environment (Section 2.4.3.3), economic (Section 2.4.3.4), and social (Section 2.4.3.5) assessments.

2.4.3.2 SUSTAINABILITY ASSESSMENTS

The review uncovered only two sustainability assessments of electricity generation systems. Many described their studies as sustainability assessments, but included only environmental, or economic and environmental, impacts. The most significant was the Databases and Methodologies for Comparative Assessment of Different Energy Sources (or DECADES) project. Initiation of the DECADES project, in 1992, was by the collaboration of (Rogner and Khan (1998)):

- International Atomic Energy Agency (IAEA);
- European Commission (EC);

†††††† For example, the Osborne Cogeneration plant in South Australia shares steam between its electricity generation needs and a soda ash plant (see www.penrice.com.au).

- United Nations Economic and Social Council for Asia and the Pacific (ESCAP);
- Institute for Applied Systems Analysis (IIASA);
- World Bank (IBRD);
- Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD/NEA);
- Organisation of Petroleum Exporting Countries (OPEC);
- United Nations Industrial Development Organisation (UNIDO); and
- World Meteorological Organisation (WMO).

The DECADES project provides background data for the development of sustainable electricity systems by governments and regulators. The DECADES project (IAEA (2000)) utilised a full energy chain (FENCH) technique to determine the sustainability impacts of a number of electricity generation technologies, including black coal and natural gas systems. The FENCH technique ignores the sustainability impacts due to construction and decommissioning of the system, and all materials consumed by the system, apart from the fuel consumed in the electricity generation activity, and is thus a subset of the 'life-cycle' perspective (IAEA (2000)). The methodology was designed for application in electricity generation sector design, and utilises the concept of valuation of environmental and social impacts to generate impact-cost of production aggregates for comparisons of the strategy options. Valuing environmental and social impacts may enable the comparison of impacts on a consistent basis, and may enhance usage and acceptability of environmental and social impacts into evaluations (IAEA (2000)). However (IAEA (2000)):

a. impacts not directly linked to a market proved difficult to cost (i.e. building damage and loss of agricultural production are linked to a market, but visual amenity is not);

b. costs for the same impact vary with location (i.e. urban-rural, or different countries);

c. impacts occurring in the future were under-represented (as future impact-costs are discounted); and

d. the results for some situations provided non-optimal solutions.

The validity of this valuation procedure was the subject of much research in both the U.S.A. and Europe (IAEA (2000)). Figure 2.4.1 shows an example of results obtained from this study (before valuation). The study has also produced a database for sustainability impact data for various electricity generation technologies and fuels, the Reference Technology Database. The sustainability impacts included: climate change, acidification, photochemical smog, particulates, radioactive releases, water pollution (thermal and chemical), solid wastes, resource depletion, visual amenity, employment, and community relations (IAEA (2000)).

Another, much less comprehensive study (Leca *et al.* (2002)), produced for an eastern-European country (i.e. a former planned economy) a comparison of the relative sustainability impacts of investment options for upgrading their electricity generation capacity. The sustainability indicators used were: net present cost, GDP share, investment flexibility, fuel diversity (economic); CO_2, NO_x, and SO_2 emissions (environmental); employment to investment ratio, and technology acceptance ratio (social). The technology acceptance ratio is the sum of ratios of acceptance for each type of technology. Ratios are the proportion of population that do not oppose the use of each technology. The study used the generation plant alone, rather than the 'life-cycle' perspective system. The sustainability of each system was determined using a multi-criteria optimisation procedure (see Section 2.3.4), which considered a set number of given scenarios. The practitioners set the criteria using their values. For example,

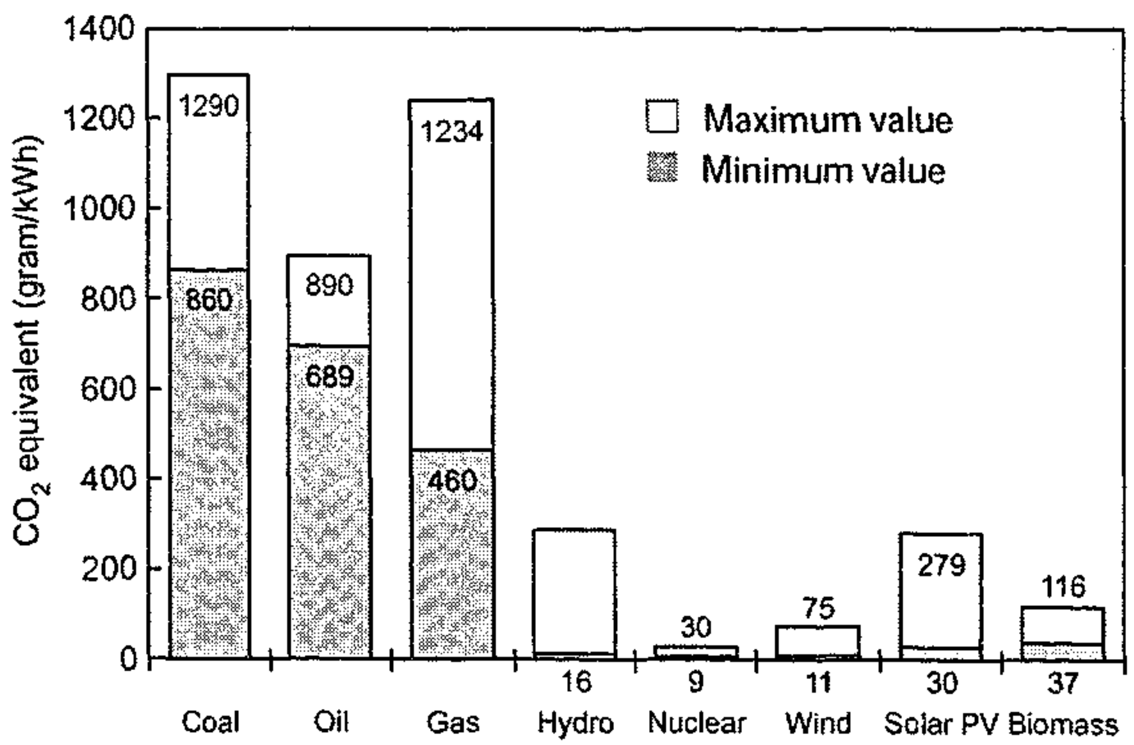

Figure 2.4.1: Comparative full-fuel cycle, greenhouse gas emissions of selected electricity generation systems (Rogner and Khan (1998)). The units g per kWh = kg per MWh.

the net present cost (18 %) had highest importance, while technology acceptance (3 %) had lowest importance. It was recognised that in other countries a lack of technology acceptance may negate any other benefits. They developed four scenarios of future requirements for electricity generation capacity, based on a perceived rate of economic growth: fast, moderate, slow, and pessimistic. The scenarios were set for 2025, 25 years after the completion of the analysis, and considered a number of projects under construction, some planned for development, and some proposed for the future. The favoured scenario included the upgrade of current coal plants, and the addition of gas-fired combined cycle units.

2.4.3.3 ENVIRONMENTAL ASSESSMENTS

There are great numbers of environmental assessments of electricity generation systems. Consequently, to keep this review manageable, only a few will be included, with similar studies provided as references.

The first major study to cover the complete fuel cycle was the COMPASS project, by the Organisation for Economic Cooperation and Development (OECD) (OECD (1985)). This study identified the environmental impacts due to electricity generation from fossil fuels as: land and water use, air emissions, long range transport and deposition of air pollutants, local climatic and visual effects from cooling towers, solid waste and ash disposal, and noise. It also noted that impacts occurred before and after generation, during the processes of mining or production, refining or processing, transportation to the generator, and transmission to the customer. Also included were other forms of electricity generation (nuclear, geothermal, biomass, solar, hydro and wind). The study did not attempt to quantify any impacts.

In response to the needs of governments to produce country 'greenhouse gas' emissions reports (e.g. AGO (1999), DoE (U.K.) (1998), EPA (U.S.A.) (2000)), some industries have produced their own such reports (e.g. AGA (1997), APPEA (1999), Lowe (1998), SECV (1992)). The categories in these major inventories are either too broad (i.e. APPEA (1999) includes oil and gas), or too narrow (i.e. SECV (1992) includes only generation) to discuss the environmental impacts of electricity generation systems using a particular fuel, with the 'life-cycle' perspective.

The International Energy Agency (IEA) created the Greenhouse Gas R&D Programme (IEAGHG) in 1991 to identify and evaluate technologies for reducing emissions of greenhouse gases arising from use of fossil fuels (IEAGHG (2000)). They examined the capture and storage of CO_2 and other atmospheric pollutants. Additionally, they produced a comparison of the greenhouse gas emissions of the generation step, without CO_2 capture, for a coal fired steam turbine (ST), natural gas combined cycle (CCGT), integrated coal gasification combined cycle (IGCC) and carbon dioxide recycle system (IEAGHG (2000)).

In the 1990s many 'greenhouse gas' studies, using the 'life-cycle' perspective, appeared. For example, the OECD and International Energy Agency (IEA) in 1992 held the 'Expert Workshop on Life-Cycle Analysis of Energy Systems' included studies for fossil and nuclear fuels, as well as photovoltaic systems (Baumann and Hill (1992), Eyre and Holland (1992), Yasukawa *et al.* (1992)). Other examples include:

a. Central Research Institute of the Electric Power Industry (CRIEPI) in Japan (CRIEPI (1994));

b. Saskatchewan Energy Conservation and Development Authority (SECDA) in Canada (Macdonald *et al.* (1996));

c. Paul Scherrer Institut (PSI) in Switzerland (Dones and Gantner (1996)); and

d. Alberta Department of Energy (Macdonald *et al.* (1996)), included separation of upstream and combustion emissions (see Figure 2.4.2).

e. Oil Industry Group in Japan (Ogawa and Yoon (1998)).

In 1995, a study by the Energy Information Agency (EIA) in the U.S.A. prepared a report on the monetary valuation, by the various state authorities, of environmental impacts incurred by steam-electric generators (Energy Information Agency (U.S.A.) (1995)). This study identified, but did not quantify or aggregate the environmental impacts. Similar studies using valuation include Office of Technology Assessment (1994) and Watkiss and Forster (2000).

In 1999, Vattenfall produced a comparative study with 'life cycle' perspective boundaries (Vattenfall (1999)). It contains comparisons based on emissions of CO_2, SO_2 and NO_x, consumption of copper, and land use. Generation technologies considered were hydro, nuclear, biofuel[‡‡‡‡‡‡], combined heat and power (CHP), wind,

[‡‡‡‡‡‡] Biofuel refers to unprocessed organic fuels, such as wood, straw and bagasse.

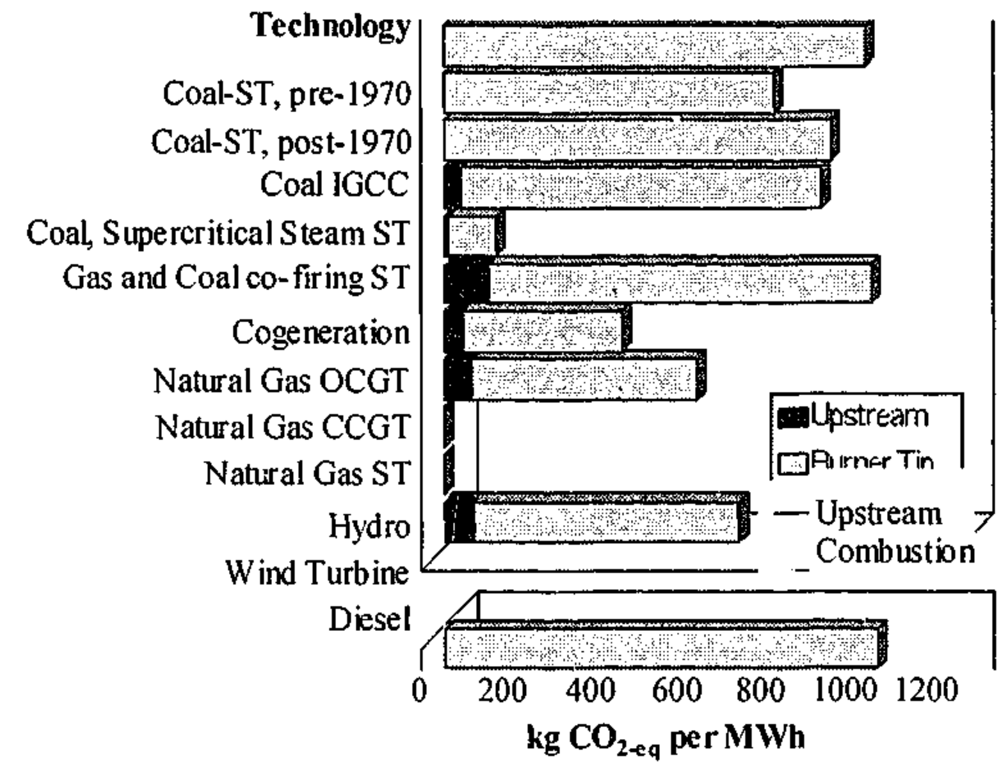

Figure 2.4.2: Comparative full-fuel cycle, greenhouse gas emissions of selected electricity generation systems (Macdonald *et al.* (1996)). ST = steam turbine, IGCC = integrated combined cycle gas turbine, OCGT = open cycle gas turbine and CCGT = combined cycle gas turbine (see Glossary for explanations).

solar, oil condensing, natural gas combined-cycle (CCGT), fuel cells, coal fired steam turbine (ST), and open cycle gas turbines (GT). This study determined that the open cycle gas turbines (GT) (used for backup generation in the event of a shortfall in supply) produced the greatest emissions of CO_2 and NO_x per kWh of electricity supplied to customers, while the coal fired ST produced the greatest SO_2 emissions. The study also found that the open cycle gas turbines (GT) and solar power consume the most copper, and the biofuelled CHP and wind power require the greatest land area. They concluded that generation from fossil fuels was far more damaging, based on the considered variables, than their generation mix of hydro and nuclear.

National Renewable Energy Laboratory (NREL) has produced several studies of electricity generation systems with 'life cycle' boundaries (e.g. Spath *et al.* (1999)). This example compared three high rank black coal generation options:

i. the current average (ST with limestone desulphurisation and baghouse particulate filter);

ii. a plant which meets the U.S.A.'s New Source Performance Standards (NSPS) (same design but more efficient desulphurisation and filters, and low NO_x burners); and

iii. the Low Emission Boiler System (LEBS) (ST with low NO_x burners, catalyst SO_2 and NO_x removal, sulphur (or sulphuric acid) generation, and baghouse filter).

Data collection is extensive, but the Impact Assessment stage is limited to a qualitative discussion, with only greenhouse gas emissions treated quantitatively.

In Australia, studies have occurred of greenhouse gas emissions during the generation step (for example: ACA (1999) and AGO (1999)) and with extended boundaries (for example: BHP Research (1999), AGA (2000), Evans (1995) and Woodside Energy Ltd. (1998a)). The extended boundary studies all include greenhouse gas emissions and most include emissions of other atmospheric pollutants. The study by Evans, through the Cooperative Research Centre: New Technologies for Power Generation from Low-Rank Coal, considered only Victorian systems delivering electricity to Melbourne (Evans (1995)). CSIRO (Australia) completed a study for Woodside Energy Ltd. in 1996 (Woodside Energy Ltd. (1998a)). This study considered the greenhouse gas emissions from electricity generation in Japan of: black coal from the Hunter Valley (NSW), liquefied natural gas (LNG) from the North West Shelf (WA), and oil from the Middle East. The study found that coal produced the highest greenhouse gas emissions per MWh of electricity generated (865 kg $CO_{2\text{-}e}$ per MWh), while LNG produced the least (493 kg $CO_{2\text{-}e}$ per MWh). These figures are consistent with previous results (see Figure 2.4.1 and Figure 2.4.2). The analysis of coal includes methane emissions from the coal mine, but excludes emissions observed to occur from the decomposition and spontaneous combustion of spoil and washery rejects piles. The analysis of LNG uses operating data from Woodside's North West Shelf LNG plant. LNG transport is by dedicated ocean carrier, while coal transport is by rail to port and ship to Japan. The LNG generation plant is a CCGT, while the coal generator is a supercritical ST, with post combustion SO_2 and NO_x removal. Approximately 91 % and 77% of the emissions were due to the power plant, for the black coal and LNG systems respectively. In 1998, CSIRO completed a similar study for natural gas and nuclear fuels (Woodside Ener gy Ltd. (1998a)). In this study, the natural gas fuelled open cycle gas turbine (OCGT) ould emit more greenhouse gases than a black coal system, but a CCGT will emit far less (c.f. Figure 2.4.1 and Figure 2.4.2). The nuclear systems

produced negligible quantities of greenhouse gases.

BHP Research and the Australian Coal Association Research Project (ACARP) completed studies on steel and electricity production with 'life-cycle' boundaries (BHP Research (1999) and BHP Minerals Technology (2001)). They included comparisons of electricity production from 10 different technologies, including black coal fired ST and clean coal technologies, and natural gas open and combined cycles. The indicators included were resource energy, greenhouse gas, NO_x, SO_2 and particulates emissions, and fresh water consumption. The results of this report are similar to those produced by other groups. The greenhouse gas emissions of the open cycle system studied are 20 % lower than that reported in other studies (Macdonald *et al.* (1996), Vattenfall (1999), Woodside Energy Ltd. (1998a)). The study ignores dust emissions from coal mining, and losses during electricity transmission. Moreover, the methane emission calculation for coal mining was lacking in detail.

In 2000 the Australian Gas Association (AGA) released a study of natural gas with 'life-cycle' boundaries (AGA (2000)), which also contained a comparative study of electricity production using natural gas, and black and brown coal. The comparison shows that for Australia, CCGT systems produce near 530 kg $CO_{2\text{-}e}$ per MWh, natural gas GT 600 to 650 kg $CO_{2\text{-}e}$ per MWh, black coal fired ST 910 kg $CO_{2\text{-}e}$ per MWh, and brown coal fired ST 1246 kg $CO_{2\text{-}e}$ per MWh. The study excludes electricity transmission, and uses an unrealistic assumption to estimate emissions from the mining and transport of both black and brown coal. Moreover, the basis for this study was Australian best practice efficiencies, rather than current practice, limiting the applicability of its results.

Much of the discussion on electricity generation sustainability involved 'greenhouse gas' emissions (IChemE (2002b), Van de Vate (1997)). However, included in at least two of the reviewed studies were indicators for climate change, acidification, eutrophication, photochemical smog formation, toxicity and particulates. Some studies also indicated that resource and water consumption, and solid waste generation were important impacts.

2.4.3.4 Economic Assessments

This section examines some important studies, which are representative of, but more comprehensive than, other published studies. Internationally, the Nuclear Energy

Agency (NEA) and International Energy Agency (IEA) produced comparisons of actual electricity generation capital and operating costs in OECD countries (i.e. western European nations, Japan and the USA), and some non-OECD countries (Nuclear Energy Agency (1998)). It considered electricity generation plant for nuclear, coal and natural gas fuels. It included conventional technologies and some advanced coal technologies. The International Energy Agency periodically updates these estimates and produces other specialised estimates (e.g. IEA (1993)).

In the USA, the Department of Energy produced comprehensive capital cost estimates of electricity generation plant (DOE (U.S.A.) (1999)). This report attempted to cost plant based on the costs of individual components. It, like the NEA study, included conventional and advanced electricity generation plants for coal fuels. For natural gas fuel, it limited its study to combined-cycle gas turbine plants, excluding both steam turbine and open-cycle gas turbine plants. It estimated both capital requirements and electricity production costs. The Department of Energy has also produced a number of other cost estimations for electricity generation (e.g. DOE (U.S.A.) (2000)).

In Australia, the Energy Research and Development Corporation produced a comprehensive study of electricity generation options it considered possible for use in the 1990's (Energy Research and Development Corporation (1992)). This study was the only independent study to include plants for Australian brown coal fuel, as well as black coal and natural gas plants. This study included electricity generation plants using both conventional and advanced technology. It estimated both capital requirements and electricity production costs. During this period, a number of other estimates were produced for Australian state governments, who were in charge of electricity network planning (i.e. Natural Resources and Environment Committee (1987)).

The economic indicators for each of these cost estimations were capital requirements and production costs (e.g. cost of electricity generated). This implies that new electricity systems must not only produce electricity at low long-term costs (production costs), but the capital requirements must be attainable for the proponent, and not place an undue burden upon them (IAEA (2000)).

None of the economic assessments encountered consider the 'life-cycle' perspective, and thus exclude the impacts of fuel production, fuel transport and electricity transmission.

2.4.3.5 *Social Assessments*

Social assessments have been uncommon for electricity generation systems, although some social impacts are included in Environmental Impact Assessments (e.g. ECNSW (1980)).

The IAEA's sustainability information document reported that the social impacts important to electricity generation are local employment and resource depletion (IAEA (2000)).

Social assessments of coal mining have highlighted that, along with local employment, health and safety is an important impact of coal mining (e.g. Minerals Council of Australia (2002)). Injuries and fatalities have important social and economic impact on communities. As coal mining is within the 'life-cycle' perspective boundary of electricity generation systems that consume coal, indicators of health and safety impacts are necessary.

None of the social assessments encountered consider the 'life-cycle' perspective, and thus exclude the impacts that occur in fuel production, fuel transport and electricity transmission.

2.4.4 Indicators for Electricity Generation

Table 2.4.1 shows the impacts determined to be important in previous sustainability, environmental, economic and social assessments from the review in Section 2.4.3. The sets of industrial indicators provided earlier (see Table 2.3.5 and Table 2.3.6) include indicators for each of these impacts. The 'Glossary' contains descriptions of many of these impacts.

The indicators are not entirely separable into the categories given. Most indicators have flow on effects contributing to other categories (e.g. increased wealth generation leads to greater tax revenue, which are used to generate social benefits). The convention adopted categorises resource depletion as an environmental indicator, although resource depletion may lead to both social and environmental impacts.

Many of the indicators in Table 2.3.5 and Table 2.3.6 have no corresponding impacts in Table 2.4.1. Existing systems require sustainability assessment to measure the performance of not only the sustainability of their operations, but also their business philosophy (i.e. the Human Rights and Society categories of indicators in Table 2.3.5

Table 2.4.1: Important indicators of sustainability, selected from a review of assessments of the impacts of electricity generation systems (naming conventions from Azapagic and Perdan (2000) and IChemE (2002b)).

Environmental Indicators	Economic Indicators	Social Indicators
Resource Depletion	Wealth Generation	Employees
Climate Change	Capital Requirements	Health and Safety
Acidification		
Eutrophication		
Photochemical Smog		
Toxicity		
Solid Waste		
Particulates		
Water Consumption		

and the Voluntary actions, Human-capital, Ethics and Welfare categories of indicators in Table 2.3.6). For a proposed system, the choice of technology is unlikely to affect business philosophy. This may not be valid if the choice results in the use of materials sourced from companies with radically different business philosophies (for example, when deciding between purchasing from companies with very different worker conditions). Similarly, if the product qualities (i.e. endurance, strength, durability, etc.) do not vary with the option chosen, then its indicators of product sustainability will also not vary (i.e. the product responsibility category of indicators in Table 2.3.5 and Environmental efficiency category of indicators in Table 2.3.6). Electricity as a product does not vary with its source technology.

2.4.5 Summary of Electricity Generation and Sustainability

The indicators presented in Table 2.4.1 are sufficient to produce a sustainability assessment of possible electricity generation systems. Examined were previous assessments of sustainability, and individual impacts of sustainability, to select these indicators. Many of these indicators are core indicators in other industrial sets of sustainability indicators.

None of the previous assessments of social and economic impacts on sustainability uses 'life-cycle' perspective boundaries, and thus they underestimate sustainability impacts.

2.5 SUMMARY OF SUSTAINABILITY

Sustainability is a concept, rather than a defined term. Often depictions of this concept have three intersecting spheres, each sphere representing a different element of sustainability (environmental, economic and social). Measuring sustainability requires the use of indicators, as they ensure relevancy to a wide range of systems and societies and allow widespread acceptability. Measuring sustainability should use 'life-cycle' boundaries as they encompass all systems dependent on the existence of the studied system, reducing the chance of shifting sustainability impacts outside a fixed boundary.

The sustainability indicators used for a sustainability assessment must be relevant to the studied system. A review of assessments of various impacts on sustainability enabled the selection of a set of indicators relevant to a sustainability assessment of electricity generation systems. The review highlights the lack of a comparison of sustainability impacts for electricity generation from Australian fossil fuels, especially brown coal. Moreover, previous social and economic assessments have lacked the use of 'life-cycle' boundaries, thus underestimating the social and economic effects of electricity generation systems.

Therefore, no previous study has compared the sustainability impacts of electricity generation systems, using sustainability indicators and a 'life-cycle' perspective, for Australian fossil fuels.

3. METHODS FOR PRODUCING SUSTAINABILITY INDICATORS

'Sustainable Development has become something of a holy grail in modern times. Rather like the Yeti and the Loch Ness Monster, there have been many claims of sightings but verification is hard to come by.'

BELL AND MORSE (2001), PG. 292.

3.1 OVERVIEW OF METHODS FOR PRODUCING SUSTAINABILITY INDICATORS

One of the important outcomes of Chapter 2 was the selection of a set of indicators for sustainability assessments of electricity generation and similar systems. Yet, there has been no mention of how to quantify these indicators. The selection of indicators is the outcome of a review of environmental, economic, social, and sustainability studies of such systems. It is also possible to simultaneously select methods used for quantification of these impacts. Chapter 2 also acknowledges that the 'life-cycle' perspective, where the collection of impacts is from cradle to grave, is essential for sustainability assessment. Only some of the methods for producing environmental indicators used the 'life-cycle' perspective. Either modification of the existing methods or generation of entirely new methods will be necessary to use this perspective. Therefore, this chapter produces a group of methods to enable the sustainability assessment of electricity generation, using indicators with 'life-cycle' coverage.

The first three sections (Sections 3.2 to 3.4) develop methods to produce environmental, economic and social welfare indicators with 'life-cycle' boundaries. These methods have varying levels of detail, depending on their relative maturity.

Section 3.5 suggests modifications necessary for the economic and social indicators to ensure the resultant set of indicators is consistent in scope, detail and accuracy.

3.2 METHODS FOR PRODUCING ENVIRONMENTAL INDICATORS

3.2.1 OVERVIEW OF METHODS FOR PRODUCING ENVIRONMENTAL INDICATORS

Chapter 2 identifies resource depletion, climate change, acidification, eutrophication, photochemical smog, toxicity, solid waste, particulates and water consumption as the most important environmental indicators of sustainability for electricity generation. Thus, this section, examines methods for the calculation of these indicators.

Section 3.2.2 examines methods for developing environmental indicators. A detailed discussion of the selected, life cycle assessment (LCA) method appears as Section 3.2.3.

3.2.2 ENVIRONMENTAL ASSESSMENT METHODS

3.2.2.1 OVERVIEW OF ENVIRONMENTAL ASSESSMENT METHODS

Most environmental assessment techniques can be traced to the late sixties (for example, Starr (1969)), as the consequences of the rapid industrial expansion in the Western world of the 1950's and 1960's became apparent. The driver for this expansion was the huge increase in consumption, especially of natural resources, stemming from rapid population growth and greater consumer confidence (Sadar (1996)). The U.S.A. released the first national policy on the environment, the 1969 National Environmental Policy Act, which also contained the concept of Environmental Impact Assessment (EIA) (Sadar (1996)). The oil crisis of the early 1970's quickened the pace of development in environmental analysis techniques, as recognition of oil resource scarcity and economic vulnerability became widespread (Boustead (1995), Sadar (1996)). During this time a number of world modelling exercises (and subsequently meetings) occurred (i.e. 1970 Club of Rome and 1972 UNEP Stockholm Conference), which lead to concern about the survival of society if it remained unchanged (Boustead (1995)). Legislation requiring some form of environmental assessment (usually EIA)

for all new projects, which had potential to cause environmental impacts, was introduced in most western (OECD) countries during the 1970's (Sadar (1996), Environment Australia (1996)).

When the 'Brundtland' report (WCED (1987)) popularised the concept of sustainability it shifted the emphasis towards the new approaches to economic development: emphasising carrying capacity and integrated resource management (Sadar (1996)). Such approaches also led to wide use of other environmental assessment techniques, including environmental audits, substance flow and life cycle assessments. Worldwide concern about the impact of development on the environment, especially climate change led to a meeting in Toronto in 1988. At Toronto, most industrialised countries agreed to voluntarily reduce carbon dioxide emissions by 20 % by 2005. In 1992, the UNCED Rio Conference discussed concerns over the sustainability of third world (or developing) countries (Sadar (1996)). The results of these meetings, while encouraging, did not lead to verifiable targets. In the UNFCCC meeting at Kyoto in 1997, many (mostly OECD) countries negotiated targets for reductions in greenhouse gas emissions.

Methods for environmental assessment can be for plants and processes, or products. Plant and process methods consider the effects for a single location or process. The most common method of this type is Environmental Impact Assessment (EIA). This is due, in part, to the statutory requirement for such an assessment as part of the project approval process in many countries (Sadar (1996)). Another important factor is its wide acceptance and standardised methodology. It is the most comprehensive method available and can consider a vast array of environmental stressors and effects. Environmental audits are also common, but to operating, rather than proposed plants (Heijungs (1995)). Environmental audits measure current performance against legislative requirements (current or proposed) or internally set targets. Risk assessments consider the impacts of low probability, high impact effects (i.e. explosions), rather than normal operating conditions (UNEP (1996)).

Product specific methods are not limited to a specific plant or location, rather they consider the stages in the production of a particular product (i.e. the 'life cycle' perspective). Some of the product specific methods used are input-output analysis, substance flow analysis, technology assessment and life cycle ~~analysis~~ assessment (LCA) (Heijungs (1995), UNEP (1996)). The use of the LCA method is becoming increasingly common, as it is the only integrated analysis method that is equipped to quantify environmental impacts from 'cradle to grave' (Consoli *et al.* (1993)). LCA, like EIA, has the advantage of wide acceptance and a standardised methodology (BHP Research (1999)).

3.2.2.2 *ENVIRONMENTAL IMPACT ASSESSMENT: ADVANTAGES AND DISADVANTAGES*

Environmental Impact Assessments (EIA) are designed to 'evaluate the environmental and related social implications (negative and positive) of carrying out a development project, of any size, before irrevocable decisions are made' (Sadar (1996)). EIA aids the improvement of internal decision making processes and the ability of third parties (such as government regulators) to make informed decisions about future projects (Sadar (1996)). In current practice, EIA has a site-specific scope, identifying the environmental impacts of one economic activity at a specific time (Kniel *et al.* (1996), UNEP (1996)). This site-specific scope gives EIA its greatest advantage, in that it can consider the entire ecosystem of the site (Sadar (1996)). The boundaries of these systems are natural (i.e. watersheds), not arbitrary or political (Sadar (1996)). Other advantages of this methodology are its ability to determine the effects of the process on each individual in the ecosystem, and to consider the resilience of these individuals and ecosystems (Sadar (1996)). If properly performed EIA can lower project costs (reduced instances of environmental disasters, court cases, and clean-ups), increase the efficiency of natural resource use, and enhance public confidence (through involvement in decision making) (Sadar (1996)). Some have used EIA for sustainability assessment (Sustainability Impact Assessments (SIA)), by including economic and social impacts in the method (George (2001)).

One disadvantage of EIA is the limitations on scope and boundary enforced by extensive legislative control (Kniel *et al.* (1996), Sadar (1996)). These limits reduce its usefulness and applicability to real situations, which have more than one process step and location. Some modifications to EIA allow the measurement of impacts across multiple locations, such as in strategic environmental assessment, but these methods are not widely used (Sadar (1996)). Another disadvantage, is that the restrictive methods legislated cannot account for all the impacts likely to occur for modern complex technologies (Kniel *et al.* (1996), Sadar (1996)). Furthermore, such studies do not consider the process technology, concentrating on the inputs and outputs, and therefore do not offer suggestions for improvement (Kniel *et al.* (1996)). Finally, the success of

any EIA depends on the existence of detailed information on the effects of the project on the local environment. Many studies require substantial additional research to overcome a lack of such information (for example, Woodside Energy Ltd. (1998b)).

In Australia, each federal and state government has its own legislation regarding EIA. From 1974[*], all projects that may, or cause another party to, affect the environment to a significant extent must submit an EIA to the relevant government environmental department[†] before the granting of approval for construction (Environment Australia (2000)). Thus, it has become a requirement to ensure project approval, rather than an objective tool for investment decisions. Some examples of legislated EIA of electricity related subjects include SECV (1973) and ECNSW (1980).

3.2.2.3 *LIFE CYCLE ~~ANALYSIS~~ ASSESSMENT: ADVANTAGES AND DISADVANTAGES*

Life cycle assessment (LCA) is an objective tool for the determination of environmental impact, to improve the environmental performance of existing systems, or to compare ~~between~~ products, processes or activities (UNEP (1996)). LCA follows the path of the target product or process from its initial beginnings to its final disposal, or 'cradle to grave' (Cowell *et al.* (1999)). For example, in steel manufacture, the 'cradle' is the mining of iron ore and the 'grave' is the dumping of scrap steel. Between these two end points there are many stages; in general this includes raw material production, processing, manufacturing, transportation and distribution, use, re-use, maintenance, recycling and final disposal (Burgess and Brennan (2001), Consoli *et al.* (1993), Nash and Stoughton (1994)). Thus, LCA determines the environmental impact with a 'life cycle' perspective.

The ~~LCA method's~~ holistic approach in LCA provides its main advantage over other techniques (UNEP (1996), Vattenfall (1999)). Other methods usually concentrate on a particular location or aspect (e.g. manufacture). The 'cradle to grave' approach, considering all stages, highlights the most environmentally important stages and allows optimisation of environmental control efforts. This is especially important given that the end-of-pipe and 'command and control' approaches have been inadequate to

[*] Refers to the Environment Protection (Impact of Proposals) Act 1974 (Commonwealth Government).

[†] If the project is wholly within one state then this is the state government environmental department. However if the project spans states then this is the federal government environmental department.

maintain or reduce emissions (Mohin (1994), Burgess (1999)).

The LCA method is largely scientific, uses quantitative system data, and produces quantitative results (UNEP (1996)), allowing the integration of its results with economic analysis techniques (Udo de Haes (1993)). Finally, even though still developing, it is an internationally standardised ~~process~~ method (ISO 14040's), ~~without the EIA method's limiting local legislative requirements~~. Therefore, results from this method are internationally recognisable and verifiable.

3.2.2.4 *Summary of Environmental Assessment Methods*

For an environmental assessment to truly represent the impacts of a product or process, it must include all the environmental impacts through its entire life cycle. LCA, which has these characteristics, is thus a more appropriate method than EIA for ~~the measuring~~ assessment of environmental ~~impacts for an assessment of~~ the sustainability of electricity generation systems.

3.2.3 Life Cycle Assessment

3.2.3.1 *Overview of Life Cycle Assessment (History)*

LCA has its origins in the late 1960's, along with most other environmental analysis techniques (see Section 2.2.1, Chapter 2). These early studies were simple, containing quantitative analyses of energy‡ and solid wastes, but with little detail on environmental effects (Burgess and Brennan (2001), Miettinen and Hämäläinen (1997)). The first of these, the ~~celebrated~~ Coca-Cola packaging study, which claimed that plastic containers were more environmentally friendly than glass, was performed by the Midwest Research Institute in 1969 (Huppes 1996)). Various studies, by the early 1970's, had estimated the energy requirements of steel, pulp and paper and petroleum refining, and provided additional data on raw material and solid waste flows (Fava and Page (1992)). The fading of the energy crisis limited the development of these types of study, and they became infrequent (Fava and Page (1992)). These pioneers in LCA were generally involved with private companies in the U.S.A. (e.g. R. G. Hunt and co-workers (1974)),

‡ For an explanation of energy analysis, see Sørensen (1979).

Sweden (G. Sundström (1971)), and Switzerland (Basler and Hoffman (1974))§, although there was some public work in the U. K. (Burgess (1999), Huppes (1996), Udo de Haes (1993)).

In the 1980s, European governments (including the Dutch and Swiss) became interested in LCA (Huppes (1996)). The Organisation for Economic Cooperation and Development (OECD), through its COMPASS project (1980-88), and the United Nations Environment Programme (UNEP) (1979-86), initiated multi-national studies (Sørensen (1992)). The isolated development of these studies often led to widely different approaches (Huppes (1996)). Thus, the results obtained from studies on the same object were often dissimilar (Burgess and Brennan (2001), Udo de Haes (1993)). Such variations prevented LCA from becoming an established part of environmental analysis (Consoli *et al.* (1993), Udo de Haes (1993), UNEP (1996)). By the end of the decade it had become apparent that acceptance would come only with a standardized methodology (Huppes (1996)).

The first stage of this process was by the Society of Environmental Toxicology and Chemistry (SETAC) in 1990, with meetings between practitioners in Europe and the U.S.A. (Huppes (1996), Udo de Haes (1993)). Despite fundamental differences in their viewpoints, the meetings lead to the development of a framework, Guidelines for Life-Cycle Assessment: A "Code of Practice" (Huppes (1996)). Superseding this book were the ISO 14040's series of standards, the development of which started barely a year later (Huppes (1996)). The release of the first of these standards, ISO 14040, was in 1997. The standards published are:

1. ISO 14040-Environmental management-Life cycle assessment-Principles and framework;
2. ISO 14041-Environmental management-Life cycle assessment-Goal and scope definition and inventory analysis;
3. ISO 14042-Environmental management-Life cycle assessment-Life cycle impact assessment;
4. ISO 14043-Environmental management-Life cycle assessment-Life cycle interpretation;

§ See Udo de Haes (1993) for references.

5. ISO/TR 14047-Environmental management-Life cycle assessment-Examples of application of ISO 14042;
6. ISO/TS 14048-Environmental management-Life cycle assessment-Data documentation format; and
7. ISO/TR 14049-Environmental management-Life cycle assessment-Examples of application of ISO 14041 to goal and scope definition and inventory analysis.

In 2001, CML published a comprehensive guide (Guinée *et al.* (2001)) on the practical application of LCA, as defined in the ISO standards.

3.2.3.2 Overview of Life Cycle Assessment (Structure)

The framework for the LCA method consists of four stages: Goal and Scope Definition, Inventory Analysis (LCI), Impact Assessment (LCIA), and Improvement Assessment. In its early forms, such as that proposed in Consoli *et al.* (1993), the progression of stages was through the first stage (i.e. after the completion of each stage the first stage was reviewed). Most studies before the publication of ISO 14040, in 1999, followed this framework. In ISO 14040, the LCA method's framework became iterative (see Figure 3.2.1), encouraging review of all stages if proven necessary during the assessment. Moreover, the intention of the fourth stage changed from the narrow assessment of possible improvements to the study subject, to a more broad 'Interpretation' of the LCA results and conclusions.

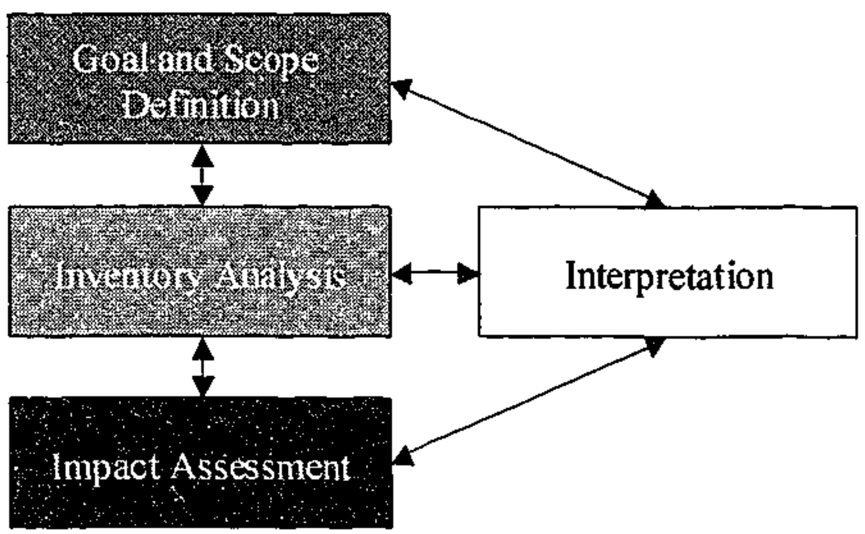

Figure 3.2.1: Framework of the LCA method according to the ISO 14040 series of standards (ISO 14040).

Some practitioners use simpler frameworks (Fava *et al.* (1991)). For example, Spath *et al.* (1999) in their LCA study of coal fuelled electricity generation used only the first two stages. However, the ISO framework is most common. Sections 3.2.3.3 to 3.2.3.6 introduce the four stages in the ISO framework of the LCA method.

3.2.3.3 Goal and Scope Definition

The first stage, Goal and Scope Definition (see ISO 14040), communicates the goal and scope of the study to readers, to provide an understanding of both the motivation for and limitations of the study. The discussion must maintain a balance between the clarity of the expressed information, and the transparency of its argument (SETAC (1998)). To ensure understanding of the goal it must contain not only the purpose of the LCA, but also the initiator of the study and the intended audience for the study report (ISO 14040). Definition of the study scope enhances understanding of the study subject and its function, and of the reporting procedure and style.

An important decision is the choice of 'functional unit'. The 'functional unit' is usually a measure of the systems output (e.g. an electricity generation system's functional unit is its output of produced electricity), and is the basis for the study results and comparisons. For example, the 'Greenhouse Gas' emissions of a shoe making system, 'A', might be 12 kg per pair of shoes. If the goal were to compare 'A' with another shoe making system, 'B', then the emissions of 'B' should also be expressed in the same form, ~~i.e.~~ e.g. 11 kg per pair of shoes. The use of the same basis allows an understandable and relevant comparison of the two system's 'Greenhouse Gas' emissions. from

Also within the bounds of definition is the development of an initial boundary for the system. ~~The~~ A pure ~~methodology of LCA~~ (comprehensive LCA) study would follow all materials consumed and emitted from the process to their ultimate environmental sources (i.e. resources in ground) and sinks (air, land, and water) (Tillman *et al.* (1994)). The nature of the modern economy is complex and interconnected. A single part, for example, may be assembled in one plant, from parts fabricated in several others, and the materials for these parts could come from other plants, and so on. The resulting LCA system, in many cases, would be world-scale (Mann *et al.* (1996)). Very large systems have so many material streams that the solution process may become difficult and time-consuming (Mohin (1994), Tillman *et al.* (1994), Burgess and Brennan (2001)), or even infeasible (Udo de Haes (2000)). Much of this system contributes relatively little to the environmental impacts of the study subject, i.e. auxiliary processes not directly influencing the study subject (Mann *et al.* (1996)), low quantity streams, or low hazard material streams. Thus, in most cases it becomes unnecessary to include all parts of the system (Udo de Haes (2000)). This boundary (the system boundary) excludes the minor contributors, to the environmental impacts of the product, from the important contributors (Consoli *et al.* (1993), Burgess and Brennan (2001)).

The system boundary is therefore a limitation, involving both value and scientific choices. This process should not remove important inputs or outputs from consideration, as inadequate boundary definition often leads to contradicting results from similar systems (Burgess and Brennan (2001), Clift (1998), Harsch *et al.* (1996), Keoleian (1993)). Methods for boundary placement are usually not entirely scientific, requiring personal judgement as to the effect of exclusions on the system. A scientific method (e.g. Lee *et al.* (1995)) would require calculation of the effect that each of the exclusions has on the results (Burgess (1999)). Thus, the individual practitioner must establish criteria for boundary placement (ISO 14040, Burgess and Brennan (2001), Lee *et al.* (1995)). Documentation of this criteria is necessary, to allow for critical review by an independent expert (ISO 14040).

The level of detail necessary to meet the study's goal and the time and funding available for the study sets the inclusiveness of the system boundary. Common boundaries include:

1. single plant or location (subsystem) (i.e. manufacturing, known as a gate-to-gate assessment)
2. simple groups of subsystems (i.e. raw material winning to manufacturing, known as cradle-to-gate assessment[**])

Other simplifications include concentrating on a single environmental impact (Udo de Haes (2000)) or on the inventory analysis stage (Mohin (1994)).

The Goal and Scope Definition only sets an initial system boundary; further information is necessary to establish that these boundaries are sufficiently inclusive. Thus, often modifications occur to this initial boundary placement in the remaining

[**] One such simple system, for energy systems, is full energy chain (FENCH) analysis, which includes mining, transport and generation subsystems (IAEA (2000)).

LCA stages.

The Goal and Scope Definition should also detail the bases for all decisions and assumptions in the remaining stages of the LCA (ISO 14040). Section 3.2.3.4 to 3.2.3.6, contains a discussion of the key decisions and assumptions within these stages.

3.2.3.4 Inventory Analysis (LCI)

The second stage, Inventory Analysis (LCI) involves the construction of a process flow chart, collection of data, redefining system boundaries, and processing the data into the form of per functional unit (~~i.e.~~ e.g. per MW) (UNEP (1996)). LCI creates a material and energy balance for the entire life of the study subject. This includes obtaining the materials crossing the system boundary, i.e. materials used in production, all transport and processing stages in production and supply to consumers, use, recycle, and disposal. Numerous rules govern the creation of this mass balance (see ISO 14041), to minimise effects on the objectivity of the result. It is important that operating data, not just design data, be gathered to account for real system operation, where deviations from design can occur, including low (or high) production rates, planned and unplanned shutdowns, and fugitive emissions. Collection of material and energy data for the mass and energy balance is difficult and time consuming; its progress determined by the accessibility of data of the systems under study, and the resources available for the practitioner. A lack of knowledge or resources often forces the neglect of some materials or material streams, or the use of an assumption in place of real data (Burgess and Brennan (2001), ISO 14040, Lindfors *et al.* (1995)). Software packages can provide data for many systems (i.e. Simapro and Umberto[††]), but this data is generally for European systems, is of varying detail, and uses generic data and assumptions, which may not be transparent, and thus introduce other errors (Treloar (2000)).

It is important to define a methodology for data collection, and the desirable level of data quality (ISO 14040). Definitions of data quality use many terms; the ISO standards recommend the following list (ISO 14040):

a. Time-related coverage: age and collection period;

b. Geographical coverage: representative area;

[††] See Simapro (2001) and Umberto (2003) for more details about this software.

c. Technological coverage: technology mix;

d. Precision: variance of the data;

e. Completeness: ratio of reporting sites to total sites;

f. Representativeness: qualitative assessment of degree to which the data reflects the true population;

g. Consistency: qualitative assessment of uniformity in methodology use; and

h. Reproducibility: qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported.

ISO 14040 recommends collection of all of this information, when the results of an LCA are for public distribution (ISO 14040). The final stage of LCA, Interpretation, may use this data quality information to estimate its influence on the results of the LCA (quality analysis).

Some subsystems ~~of the study subject's system~~ can have multiple products, e.g. a petroleum refinery might produce diesel, petrol, aircraft fuel, and any number of other products. Each product is responsible for some portion of that subsystem's inventory. Thus, it is necessary to separate, or allocate, the inventory of products used in the study ~~subject's system~~ from the remainder of the inventory.

Allocation should reflect the physical behaviour of the system (Burgess and Brennan (2001), Consoli *et al.* (1993), ISO 14041). Many parameters fit this description: i.e. economic value, mass, volume, energy or exergy content, surface area, or number of moles (Burgess (1999), Stromburg *et al.* (1997)). The final choice is often subjective or arbitrary. The results of allocation are dependent on this choice (Burgess and Brennan (2001)). Allocation based on economic value has many supporters, since it reflects the social basis for the functioning of all processes (Guinée *et al.* (2001), Stromburg *et al.* (1997)). The ISO standards (ISO 14041) recommend this method when no other method reflects the physical behaviour or other methods are inadequate. For example, this may be the case when producing two products of vastly different worth (say gold and copper), with copper present in higher proportions than gold, but gold ~~provides the greatest~~ having a higher value and driv~~es~~ing production. Thus, allocation based on economic worth more adequately represents the situation, as plant would not exist if no gold were present. This method

requires knowledge of the economic values of all products (Guinée *et al.* (2001)), and perhaps knowledge of their long-term variability. Methods that are more complex have been used, i.e. natural and physical relations of cause and effect (Stromburg *et al.* (1997))[‡‡]. Other workers have reported that the choice of allocation method affects the outcome of LCA studies (Burgess and Brennan (2001), Guinée *et al.* (2001)). Where more than one allocation method is applicable, testing of both methods is necessary, to ensure that the outcome is robust to this choice (ISO 14041). Allocation may also be required for LCA studies which include reuse or recycling of materials (ISO 14041). Avoidance of allocation is sometimes possible, by dividing the unit process into smaller sub-processes that do not require allocation, or expanding the system to include by-product stages (ISO 14041). However, this may substantially increase data requirements, and in most cases, it is easier to allocate (Stromburg *et al.* (1997)).

Another important function of the LCI is to review the placement of boundaries on the LCA system. Changes to the boundaries may be necessary if there are differences between the expected and true ~~relevance's~~ significance of material streams. For example, the data might show a stream, initially considered significant, has low impacts (UNEP (1996)). Conversely, data collection might suggest the inclusion of an initially excluded stream. The basis for any changes to the initial system boundary must be a sensitivity analysis, or other proof of insignificance to the results of the study (ISO 14041). Provision of the reasoning for each inclusion and exclusion will allow for review (ISO 14040).

The main outcome of the LCI will be the production of an inventory of material and energy ~~consumptions~~ use and emissions expressed (in kg per functional unit) ~~for the study subject's system.~~

3.2.3.5 *IMPACT ASSESSMENT (LCIA)*

The third stage of LCA, Impact Assessment, involves the conversion of the mass balance into scores for a number of defined environmental impacts. LCIA consists of two operations, classification and characterisation (ISO 14040). In addition, other operations are optional, such as normalisation and weighting (ISO 14040).

Classification involves the distribution of the study subject's inventory, prepared in the LCI stage of LCA (see Section 3.2.3.4), into impact categories (ISO 14040). Impact categories are types of environmental impacts, such as climate change and acidification.

‡‡ See Burgess and Brennan (2001) for further details on these methods.

The goal of the study will dictate the choice of impact categories. For example, if the desire is to examine the impact on the environment of a subject's 'Greenhouse Gas' emissions, then the only impact category necessary is climate change.

Impact categories may refer to any part of the environmental impacts mechanism (Udo de Haes *et al.* (1999)). The environmental mechanism is the chain of events (effects) between the process or product and a particular impact. Thus, the choice of the endpoint of the environmental mechanism may include the impact categories: damage to humans, loss of biodiversity and loss of materials (Udo de Haes *et al.* (1999)). The more usual choice is to use midpoints, such as climate change or ozone depletion, as this generally reduces the amount of specific environmental detail required.

Table 3.2.1 shows the impact categories recommended by the ISO standards. An important feature of LCA is that it includes input impacts, such as the 'resource depletion' and 'increase of land competition' impact categories, as well as output related impacts. The CML guide (Guinée *et al.* (2001)) recommends the use of the impact categories highlighted in Table 3.2.1, in all LCA studies. The final choice for environmental impact categories is up to the practitioner.

The definitions of the impact categories have only very recently been standardised (Udo de Haes *et al.* (1999)). Some traditional categories are absent from the list of standard categories (see Table 3.2.1), due to a lack of understanding of how to measure their impact. Some examples of these traditional categories are noise, odour, damage due to accident, and non-toxic human impacts (Udo de Haes *et al.* (1999)). Classification methods for the toxicity categories are still developing (Boustead (1995), Burgess (1999), Curran (1993), Udo de Haes *et al.* (1999)), and do not yet meet the ISO

Table 3.2.1: Impact categories recommended in the ISO standards (ISO 14042, Udo de Haes *et al.* (1999)). Bold categories are those recommended for use in all studies by CML (Guinée *et al.* (2001)). See 'Glossary' for more information about bold categories.

Inputs	Outputs
Extraction of biotic resources	**Climate change**
Resource depletion	**Stratospheric ozone depletion**
Land use:	**Human toxicity**
Increase of land competition	**Eco-toxicity**
Degradation of life support functions	**Photo-oxidant formation**
Bio-diversity degradation	**Acidification**
	Eutrophication

requirement that LCIA have a scientific basis (Udo de Haes *et al.* (1999)).

Many of the impacts described involve the same ~~molecular~~ species. For example, nitrogen oxides (NO_x) contribute to the acidification, photochemical smog, eutrophication, and toxicity categories. A material or emission contributing to one impact may be available to all other impacts (known as a serial mechanism), no other impact (known as a parallel mechanism), or modified such that it produces a different impact (indirect mechanism) (Gorokhov *et al.* (2002)). Some materials, or emissions, may need to combine with others to create an impact (combined mechanism) (Gorokhov *et al.* (2002)). Yet, the determination of the exact pathway of each material or emission generated by the systems would involve substantial additional assessor resources, and may prove impossible to achieve. Therefore, practitioners commonly assume that the serial mechanism applies. Consequently, the results from most LCA are high estimates of the impact, rather than necessarily the actual impact in practice.

The LCA method aggregates data by integrating across time and space (Udo de Haes *et al.* (1999), Huppes (1996)). Integration over time is valid if there is no great change in impacts between any given year and the next, i.e. steady state (Udo de Haes (1996)). Yet, in some systems there are variations in environmental effect over time. For example, the leaching of heavy metals from mining wastes decreases steadily over periods of up to several hundred thousand years (Huppes (1996), Burgess (1999)). Udo de Haes *et al.* (1999) discuss methods for dealing with such systems. Current best practice involves the use of infinite time, without discounting, with approximation used only if relevant (Udo de Haes *et al.* (1999)). Spatial aggregation is possible as the impact categories measure midpoint effects, rather than final effects (see Paragraph 3 of this section). The need for spatial differentiation is apparent for impact categories that have only local effects. Some examples are acidification (important over lakes and forests, but has little effect over the sea), photo-oxidant formation (smog precursors have little effect outside urban areas), or human toxicity (effect varies if emitted indoors or outdoors) (Udo de Haes *et al.* (1999)). For a summary of possible solutions, see Burgess and Brennan (2001).

The characterisation step involves multiplying the classified data by an equivalency factor (CF), which gives an indication of the relative impact of the substances within the classified data. Other workers have used detailed environmental models of the fate and impact of each possible material consumed or emitted to develop these CF factors

(Mohin (1994)). For example, methane (CH_4) has a global warming potential (GWP) of 21 kg CO_2/kg CH_4 (Guinée *et al.* (2001)), where GWP is measured in kg CO_2 eq. and based on methane effecting global warming for 100 years. The use of different environmental models has led to some categories having multiple sets of CF factors. This choice of CF factors from these introduces a degree of subjectivity, and therefore the decision process should be considered and transparent (ISO 14040). There has been some debate about the introduction of a scientific method for this choice (Udo de Haes (2000)).

CML recommends methods for characterisation in its Guide (Guinée *et al.* (2001), Volume 2A, Chapter 4), and provides equivalency factors for each recommended method (Guinée *et al.* (2001), Volume 2B, Chapter 4, shown here in Table 3.2.2).

Table 3.2.2: Methods for characterising impacts recommended by the CML guide (Guinée *et al.* (2001)).

Impact Category	Characterisation Method(s)
Resource depletion	Abiotic depletion potential (ADP)
Increase of land competition	un-weighted aggregation of used land ($m^2.y^{-1}$)
Climate change	GWP_{100} (Houghton *et al.*, 1994 & 1995)§§
Stratospheric ozone depletion	steady state ozone depletion potential (ODP)•••
Human toxicity	steady state human toxicity potential (HTP)†††
Eco-toxicity	separate toxicity scores for freshwater, marine and terrestrial phases†††
Photo-oxidant formation	high NO_x photochemical oxidant creation potential (POCP)‡‡‡
Acidification	average European acidification potential (AP)§§§
Eutrophication	generic eutrophication potential (EP)

Resource depletion is a category that attempts to aggregate the environmental impact due to the extraction of non-living material from the environment. Current definitions propose three subcategories:

a. deposits, which cannot be replaced (e.g. fossil fuels and mineral ores);

b. funds, which are replaced naturally over time (e.g. groundwater, sand and clay);

§§ Model developed by the Intergovernmental Panel on Climate Change (IPCC).

••• Model developed by the World Meteorological Organisation (WMO)

††† Model developed for USES 2.0 model of RIVM.

‡‡‡ Model developed by UNECE.

§§§ Model developed at IIASA (RAINS10 model).

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and

c. flows, which are continuously and completely replaced (e.g. solar energy, wind and surface water) (Udo de Haes *et al.* (1999)).

Another difficulty involves the choice of an appropriate indicator for the resource depletion category. It is desirable, for simplicity, to use a single indicator. However, this indicator must be able to account for the differences between non-renewable (deposits) and renewable (funds and flows) materials. This is difficult since the empirical verification of its validity is impossible (Finnveden (1996)). In addition, if the subcategory definitions apply different bases (i.e. present availability, possible future use, or energy potency) then different endpoints might be relevant (Udo de Haes *et al.* (1999)). In these situations, separate indicators for each basis are more relevant than an overall indicator. For some systems, these simple and complicated methods both produce similar results (Finnveden (1996)).

The most commonly used category indicator for resource depletion, consumption rate, involves the division of consumption by deposit capacity. Yet, is the appropriate ratio reference region local (i.e. coal used to coal in mine), regional (i.e. coal used to coal in region), or global (i.e. coal used to global coal resources)? Practitioners commonly use a global reference region. This introduces a new figure, global reserves, and with it come its own uncertainties. Firstly, the discovered energy resources increase by 0.8 % per year (Müller-Wenk (1998)). Secondly, the figure is often an aggregate of regional figures, compounding the individual errors, or scaled from individual country figures, without considering regional differences (such as in UNEP (1996) and Guinée (1993)). In addition, the figures do not discriminate between the high quality resources, currently utilised (i.e. coal deposits close to the surface, or light, low sulphur oil and gas), and the lower quality resources that may need to replace them (Müller-Wenk (1998)). Thus, a total resources figure overestimates the amount of useful resources. The eventual amount of resources used, the ultimately extractable reserve, is the only relevant measure of resource use (Finnveden (1996), Guinée and Heijungs (1995)). Unfortunately, data for this value is unavailable, because of its dependence on future technologies (Finnveden (1996)). Nevertheless, many LCA studies use a global reference region for resource depletion quantification (Fava *et al.* (1991), Finnveden (1996), Heijungs *et al.* (1992), Guinée and Heijungs (1995)).

Some other indicators proposed for resource depletion include rareness of resources, consumption rate, energy depletion, exergy destruction, mineral concentrations (aggregation with weighting), total material usage (aggregation without weighting), and flow use to total flow (Finnveden (1996), Udo de Haes *et al.* (1999)).

The CML guide (Guinée *et al.* (2001)) recommends the method shown in Equation 3.2.1 to produce characterisation factors for resource depletion.

$$CF_{RD,i} = \left[\left(\frac{C_{i,R}}{(R_{i,R})^2}\right) \Big/ \left(\frac{C_{Sb,R}}{(R_{Sb,R})^2}\right)\right]$$

Equation 3.2.1

where: $CF_{RD,i}$ = resource depletion equivalency factor for substance i (kg of substance i per kg of Antimony (Sb.)[****]; $C_{i,R}$ and $C_{Sb,R}$ = consumption of substance i and Sb. in region R (i.e. the world) for one year (kg per annum); and $R_{i,R}$ and $R_{Sb,R}$ = remaining reserve of substance[††††] i and Sb. in region R.

Other commonly used variants include energy and exergy content measures (see Equation 3.2.2).

$$EDP = \text{Exergy Depletion (MJ per kg)} \quad \text{or} \quad \text{Energy Content (MJ per kg)}$$

Equation 3.2.2

where: EDP = Exergy or Energy Depletion Potential (MJ per kg).

All of these methods fail to measure the impacts of differences in abundance and social value, which are the bases of the resource depletion category (Finnveden (1996), Guinée and Heijungs (1995)). Thus, debate continues as to the applicability of these methods to measure the impact of resource depletion (Guinée *et al.* (2001)). Consequently, the validity of the measures as indicators of sustainability is questionable.

Section 2.4 (Chapter 2) indicates that each of the indicators in Table 3.2.2 are important for electricity generation systems, except increase in land competition and stratospheric ozone depletion. For each of these indicators, characterisation involves:

**** Antimony is the reference substance for the resource depletion impact category.

†††† Includes all mineral sources.

$$ICS_{a,c} = m_c \, x \, CF_{a,c}$$

Equation 3.2.3

where: $ICS_{a,c}$ = characterised score for impact category a and substance c for the study subject's system under study, expressed relative to a ~~(kg of impact category a's~~ reference substance); m_c = mass of substance c emitted or consumed in the study subject's system (kg c per functional unit); $CF_{a,c}$ = characterisation factor for impact category a and substance c (kg c per kg of impact category a's reference substance).

Three more impacts are important for electricity generation: solid waste, particulates, and water depletion. Water depletion is not an impact category in the ISO standard (ISO 14042), but is included as a flow in resource depletion. In the dry Australian conditions, there is increased competition for surface water and relatively slow rates of replenishment (Lundie *et al.* (2000)). Thus, the definition of surface water as a flow is questionable. Other substance categorisation difficulties may also occur. For example, groundwater is a fund if removed in sustainable quantities, but over-consumption could produce irreversible depletion. Thus, separation of water depletion from the resource depletion category is desirable (Lundie *et al.* (2000)). Due to the lack of an accepted characterisation method, aggregation applies no weighting to contributors to these three categories. Thus, all waters (surface, treated, or ground) are equivalent (characterisation factors = 1). Similarly, all particulates (dusts and particulates), and solid wastes (i.e. coal, ash, general waste, etc.) are equivalent for their categories.

Quantification ~~Production~~ of the total impact score involves summing the resultant values, after characterisation, for each impact category (Equation 3.2.4). This total impact score represents the magnitude of each impact produced by the system.

$$ICS_a = \sum_{c=1}^{C_T} ICS_{a,c} = \sum_{c=1}^{C_T} m_c \, x \, CF_{a,c}$$

Equation 3.2.4

where: ICS_a = impact category score for impact category a for the study subject's system (kg of impact category a's reference substance per functional unit); and C_T is the total number of substances.

An optional further step involves normalisation of the impact category values (ISO 14040). This process normally involves dividing by a representative value, i.e. the impact category score for the world or Australia (see Equation 3.2.5). This produces an indication of the fractional contribution of the system's environmental impact to the overall contributions from all sources in that region. For example, the emissions of greenhouse gases from a process might be 40 t of CO_2 equivalents per year after characterisation, and 0.1 % of the national yearly emissions after normalisation. In some cases, a local, national or regional representative value is of more value than the global one. This is especially true for localised impacts, such as photo-oxidant formation, acidification, and eutrophication.

$$ICS_a^{R,N} = \frac{ICS_a}{ICS_a^R}$$

Equation 3.2.5

where: $ICS_a^{R,N}$ = impact category score a for the study subject's system, normalised for region R (i.e. Australia) (kg of impact category a's reference substance per functional unit per kg of impact category a's reference substance emitted or consumed in region R over one year); ICS_a = impact category score for impact category a for the study subject's system (kg of impact category a's reference substance per functional unit); ICS_a^R = impact category score a for region R over one year (kg of impact category a's reference substance emitted or consumed in region R over one year).

There is a lack of consensus on the appropriateness of the normalisation method (Burgess (1999), Ekvall *et al.* (1997)), and the reference area and data sources it uses (Burgess (1999), Udo de Haes (1996)). However, the CML guide strongly recommends its use in any LCA (Guinée *et al.* (2001)).

Weighting[****] produces a single value, often named as an environmental index, from the impact category results. The weighting process multiplies each impact category score by a weighting factor, chosen to indicate that impact categories relative

[****] Eco-indicator 99 and EPS include operational weighting. The CML guide discourages 'straight forward' use of these methods (Guinée *et al.* (2001)), and ISO 14042 forbids their use in public studies.

importance (see Equation 3.2.6). In most cases, development of weighting factors is by a panel of experts or diverse interested parties, based on their opinion of the importance of these impacts to society. There are many sets of weighting factors available[§§§§], but there is no consensus on the definitive set (ISO 14040, UNEP (1996)). ISO 14040 states 'there is no scientific basis for the determination of an overall environmental index'. For this reason there is no globally acceptable set of weighting factors, nor is their development likely, since they would need to be able to vary with location, time, culture, and changing values (Burgess (1999), Udo de Haes (2000), Udo de Haes *et al.* (1999)). Moreover, the ISO standards require the presentation of data generated before this step within the report (ISO 14040). Therefore, the CML guide states that weighting is not applicable in most LCA studies (Guinée *et al.* (2001)).

$$OEI = \sum_{i=1}^{I_T} WF_i \; x \; ICS_i$$

Equation 3.2.6

where OEI = overall environmental index; WF_i = weighting factor for impact category i; ICS_i = impact category score for impact category i for the study subject's system (kg of impact category a's reference substance per functional unit); and I_T = total number of impact categories.

Alternative approaches for aggregation include the 'multi-criterion' approach, and valuation (see Clift (1998) and Section 2.3.5, Chapter 2).

LCIA is continually developing (ISO 14040, Spath *et al.* (1999)). The ISO 14042 standard contains the concepts, technical framework, and methodological guidelines and requirements (Udo de Haes (2000)). However, to allow the freedom to match the methodology used with the goal and scope defined, and for changes brought about by technological developments, there is no prescribed method (ISO 14040). Thus, ISO/TR 14047 provides illustrative examples (Udo de Haes (2000)), and the CML guide (Guinée *et al.* (2001)) provides further guidance on how to apply LCIA.

The main outcome of this stage is a set of impact category results, for use as indicators of environmental sustainability.

[§§§§] For discussion of various weighting sets, see Burgess (1999).

3.2.3.6 Interpretation

The last stage, Interpretation (see ISO 14043) involves combining the outcomes of the other three stages to provide conclusions and recommendations consistent with the goal and scope (ISO 14040). Interpretation may also involve an iterative review of the data analysed in the other stages (ISO 14040). Consequently, it may include comparisons of the relative importance of different impacts and of different systems. Examination of the relative contributions of different subsystems within the study subject's system may also highlight opportunities for the improvement of impacts in individual subsystems. Interpretation may also include: quantitative assessments of completeness (the inclusiveness of the LCA system boundary); sensitivity (the effect of data input and methodological decisions within the LCA), uncertainty (the variability of results due to variability in data used); gravity (determines data with greatest contribution); or consistency (of criteria used for decisions) analyses (ISO 14040). A sensitivity analysis estimates the influence of key decisions within the assessment, such as the choice of allocation and characterisation factor methods, on the environmental indicators, by showing the outcome from each probable choice. Most LCA studies are simplifications, for they contain assumptions and often ignore subsystems for which there is a lack of knowledge, or which are difficult to calculate (Weidema (2000)). Thus, in all LCA studies, an estimate of the uncertainty of its results is necessary (Weidema (2000)). Section 3.2.3.7 examines uncertainty analysis for LCA. The CML guide and ISO 14040 recommend the use of these two analyses when disclosing LCA results to the public (Guinée *et al.* (2001), ISO 14040).

Under the SETAC system (Consoli *et al.* (1993)), this last stage was 'Improvement Assessment' and had a different focus. As the name suggests, this was the part of the study designed to suggest possible improvements in the product or process. Improvement assessment reduces the possibility of using LCAs to justify the current system, and highlight possible improvements in all systems (Consoli *et al.* (1993)). An improvement in one subsystem does not automatically produce an overall improvement, as impacts may increase in other subsystems (Sullivan and Young (1995)). For example, the introduction of a recyclable product reduces the demand for new products (thus lessens upstream impacts), but requires the introduction of a new collection and processing system (thus increases impacts). Thus, testing improvement options may require modifications to the study subject's system boundary. Consequently, the other

stages of the LCA method may also require review.

The outcome of this stage of the LCA is a set of conclusions and recommendations about the study subject's impact on the environment, and an analysis of the robustness of the indicators from which they derive.

3.2.3.7 Review of Uncertainty Methods

3.2.3.7.1 Introduction

Traditional methods for determining the range of a result (known as error analysis), used in other types of assessment, have proven inadequate for LCA, as they cannot include so many different types of uncertainty (Berg *et al.* (1999), Guinée *et al.* (2001)). Thus, substantial effort has occurred to develop a generalised method for LCA.

The International Organization for Standardization (ISO) 14040s series of standards recommend that practitioners document data quality requirements in the study's Goal and Scope Definition (ISO 14040) (see Section 3.2.3.4, points a.-h.). If there is a need for an accurate and detailed study, ISO 14041 recommends three types of analyses: gravity, uncertainty and sensitivity (ISO 14040, ISO 14041, see Section 3.2.3.6). In addition, the CML guide (Guinée *et al.* (2001)) recommends the optional use of a 'Pedigree Matrix' and/or one of the proposed uncertainty frameworks (e.g. Berg *et al.* (1999), or Huijbregts (1998)).

The Society of Environmental Toxicology and Chemistry (SETAC) European working group on 'Data Availability and Data Quality' (Huijbregts *et al.* (2001)) provide both a framework for uncertainty, and possible methods to calculate data uncertainty. The framework classifies data uncertainty into 'data inaccuracy' and 'lack of specific data' (i.e. data gaps and unrepresentative data). They recommend using either input-output modelling, data from similar products, or mass balances to fill data gaps. They recommend estimation of unrepresentative data uncertainty using uncertainty factors, obtained through further analysis of material inputs and outputs, and account for temporal, geographical and technological differences, using the pedigree matrix of Weidema (Table 3.2.3). Estimation of total uncertainty uses the Monte Carlo simulation method (see Section 3.2.3.7.2). Empirical justification of the uncertainty factors and data ranges is also necessary to ensure the relevance of the conclusions. This is a substantial task for even a simple LCA study.

Table 3.2.3: Matrix of indicator scores ('pedigree matrix') for rating the quality performance of data (Weidema and Wesnæs (1996)).

	Indicator Score				
	1	2	3	4	5
Independent of the study in which the data are applied:					
Reliability of the source	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by an industrial expert)	Non-qualified estimate or unknown origin
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but for shorter periods	Representative data from a smaller number of sites and shorter periods, or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Dependent on the goal and scope of the study:					
Temporal correlation	Less than 3 years of difference to year of study	Less than 6 years of difference to year of study	Less than 10 years of difference to year of study	Less than 15 years of difference to year of study	Age unknown or more than 15 years of difference to year of study
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from an unknown area or with very different production conditions
Technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes and materials but from same technology	Unknown technology or data on related processes or materials but from different technology

A review of uncertainty analysis methods indicated that there were three types: a quantitative analysis considering only numerical uncertainties in input data (see Section 3.2.3.7.2); a qualitative analysis using indicators to consider types of uncertainty that are difficult to quantify (see Section 3.2.3.7.3); and a quantitative analysis, which attempts to convert qualitative uncertainty, and combine it with quantitative uncertainty (see Section 3.2.3.7.4).

3.2.3.7.2 Numerical Uncertainty

Quantitative analysis methods use input data variability information to obtain a cumulative uncertainty value for an output, using uncertainty propagation. Proposed

analytical methods for uncertainty propagation include uncertainty propagation, interval methods, fuzzy logic simulations, and Bayesian statistics (Huijbregts (1998)). More common is the use of stochastic models, such as Monte Carlo (Huijbregts (1998), Kennedy *et al.* (1996)) or its modified form Latin Hypercube (Huijbregts (1998)) simulation, as they are able to include any number of different probability distributions for the individual data points (Huijbregts (1998)). These stochastic methods randomly vary all individual data values, using their individual uncertainty distributions. For example, data point 'A' has a mean at 100, with a distribution such that the probability that it is 100 is 50 %, while the probability that it is 95 is 12 %. Then, for 100 iterations, the stochastic method will use a value of 100 for this data point in approximately 50 iterations, and a value of 95 in approximately 12 iterations. As the calculation involves many such data points, all varying independently from each other, the result calculated will also vary. The collected results from all these iterations form a new profile, which represents the uncertainty of the result.

The Monte Carlo method uses actual ranges and probability distributions of the collected data, when available. However, data limitations often necessitate the use of 'rules of thumb' (i.e. Finnveden and Lindfors (1998), Lindfors *et al.* (1995)) to produce likely ranges and a probability profile for each data source. The most common probability profiles are triangular, uniform, normal, and log-normal (see Figure 3.2.2).

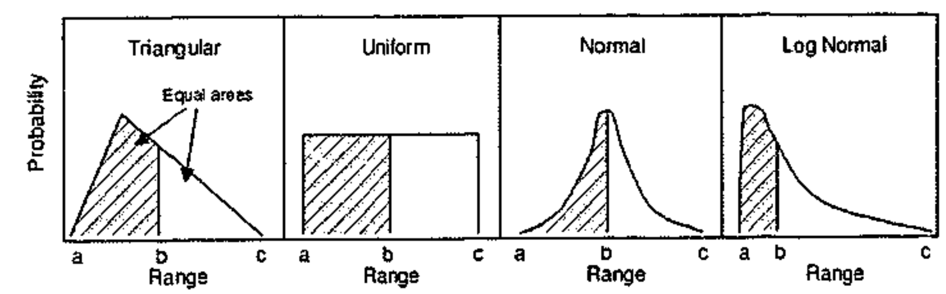

Figure 3.2.2: Four common probability distributions from industrial measurements (a = minimum, b = average, c = maximum).

Despite the seeming completeness of such methods, they do suffer a number of limitations. Firstly, they consider only one type of data uncertainty, variability from the true mean, ignoring the data's fitness for purpose, and most importantly, how accurately the system modelled in the LCA matches reality (Berg *et al.* (1999), Rousseaux *et al.* (2001)). Secondly, combining the uncertainties of the different types of data used at different points in the LCA model has proven difficult (Berg *et al.* (1999), Maurice *et* *al.* (2000)), e.g. data uncertainty and uncertainty due to allocation between products. Thirdly, the uncertainty of the LCA model itself is unknown (Guinée *et al.* (2001)), and testing against real systems is impossible, as the outputs have no defined spatial or temporal characteristics (Berg *et al.* (1999)). Lastly, a final uncertainty value can only be calculated with confidence for a specific impact category (Berg *et al.* (1999)). While postulation of the relative contributions of specific impacts to total environmental impact is possible, for example by reference to expert opinion. such relativities are necessarily subjective and their uncertainty cannot be quantified on a scientific basis.

3.2.3.7.3 Qualitative Uncertainty

To measure the qualitative uncertainty in an LCA model a score is given for each of the attributes of the system that add to uncertainty; a lower score in most cases represents higher quality. These scores are of three levels (Berg *et al.* (1999)):

- data level (individual data sources)
    - Example indicators: see Table 3.2.3.
- process level (physical or notional subsections of the system)
    - Example indicators:
        - completeness (all flows considered in process); and
        - applicability of assumptions for allocation and aggregation.
- system level
    - Example indicators:
        - completeness (all processes considered),
        - applicability of assumptions for aggregation and impact category choices.

This is the 'Pedigree Matrix' method (Funtowicz and Ravetz (1990)).

There are many groups of indicators to describe the quality of an LCA system. For example, Weidema and Wesnæs (1996) proposed the indicators shown in Table 3.2.3. Each of these indicators is data level only, while others (i.e. Rousseaux *et al.* (2001), or Wrisberg (1997)) list indicators at many levels. Some declare that aggregation of these

indicators is inappropriate because the scores do not represent an amount of quality (i.e. Weidema and Wesnaes (1996), Weidema (1998), or Coulon et al. (1997)). Thus, they claim that the aggregated scores have no meaning (i.e. a worse score for one system over another does not imply it has worst data quality). Other researchers (i.e. Wrisberg (1997)) and Lindeijer *et al.*[*****] suggest otherwise, claiming the aggregate score is an indicator of data quality; rather than a measure.

In one method, proposed by Wrisberg (1997), aggregation of quality indicators uses equal weights for all environmental flows. Consider for example, the case where an environmental impact result is developed from two material flows, with data quality scores of (3, 2, 4, 1, 1) and (1, 1, 2, 3, 4), for the five indicators respectively, and contributions of 33 % and 67 % of the environmental impact result respectively. The final indicator scores will equal the sum of the indicators divided by two, or (2, 1.5, 3, 2, 2.5).

Another method, proposed by Rousseaux *et al.* (2001), compares the quality performance of each data point to some decided target quality goal score (e.g. 2 out of 5). The percentage of data points that pass this criterion (called 'Acceptability'), determines the performance of a particular process or system. For example, a hypothetical process A has three data points with quality indicator scores of (1, 2, 1, 3, 4) for point B, (2, 3, 2, 4, 1) for point C, and (3, 3, 3, 3, 3) for point D. The chosen quality goal score is 2. For the first indicator: point B's (1) and C's (2) score passes, but point D's score (3) fails. Thus, the 'acceptability' of process A's first indicator is 66 %[†††††]. The ratio of the quality score variance to the average quality score is helpful when attempting to reduce qualitative uncertainty (i.e. indicator scores). Variance here is the sum of each points difference from the mean divided by the number of points. Using the above example, the average of process A's first indicator is 2, its variance is 2/3, and thus its variability ratio is 33%[‡‡‡‡‡]. If this ratio is high, then the quality scores have a wide spread, and may include some very 'good' (1) and 'bad' (5) scores. In this case, improving the total quality involves reducing the number of 'bad' scores. When the ratio is low, then the quality scores are in a narrow range and improving the total

***** From: Lindeijer, E., Berg, N.W. van den and Huppes G. (1997), *Procedure for Data Quality Assessment*, Report for Rioned (in Dutch), September (discussed in Berg *et al.* (1999)).

††††† For the remainder of the indicators the 'acceptability's' are 33 %, 66 %, 0 %, and 33 %.

‡‡‡‡‡ For the remainder of the indicators the 'reliability's' are 8 %, 33 %, 7 %, and 58 %.

data quality score requires changing greater numbers of data points.

3.2.3.7.4 Methods for Combining Numerical and Qualitative Uncertainty

The use of numerical and qualitative uncertainty results, obtained from the methods shown in Sections 3.2.3.7.2 and 3.2.3.7.3, together may indicate uncertainty in impact results. Alternatively, conversion of an individual data point's qualitative uncertainty into a quantitative uncertainty profile (called 'additional uncertainty') allows addition to the data point's numerical uncertainty profile (see Section 3.2.3.7.2). Using a stochastic method (see Section 3.2.3.7.2) generates a total system uncertainty profile from this summed profile. These methods can include the converted process and system level qualitative uncertainties at the appropriate points in the calculation (i.e. to the estimated process and system uncertainties).

Three different methods have been proposed for the conversion of qualitative uncertainty into additional uncertainty: Beta probability functions (Kennedy *et al.* (1996)); additional estimated uncertainty ranges (twice the coefficient of variation[§§§§§]) for each type of data elements (Meier (1997)); and obtaining estimates of variation due to the problem indicated[******] (Weidema and Wesnaes (1996)). The first method (of Kennedy *et al.* (Kennedy *et al.* (1996))) integrates a chosen list of indicators through a parameter, x, known as the percent of attainable data quality (Equation 3.2.7). It does not recommend a prescribed set of qualitative indicators, but that they develop from previous experience of using the method. For example, a data point has a value of 100, with quality scores of (2,2,3,2,1) for five indicators. The sum of quality scores is 10, the sum of maximum quality scores is 25 (maximum score for each indicator is 5), and the sum of minimum quality scores is 5 (minimum score for each indicator is 1). Thus x equals (10-5)/(25-5) times 100 = 25 %. Table 3.2.4 provides the data quality indicator (I) (example I is 2). This indicator (I) creates one or more Beta probability distributions, which are modified normal distributions, described using two shape parameters (α and β) and its extents (A and B). Estimating these parameters from I

§§§§§ The coefficient of variation is equal to the standard deviation divided by the mean value.

****** For example, an update to the energy consumption data taken from an older process could use the increased efficiency of the new process. In the general case, this requires additional research into each data point, and thus considerable additional resources may be necessary.

Table 3.2.4: Table to obtain the shape parameters from I for use in the data quality indicator method of Kennedy *et al.* (1996).

% of Attainable Data Quality (x)	Aggregated Data Quality Indicator (I)	Shape Parameters		Extents (% variation from mean)	
		α	β	A	B
100	5	5	5	-10	+10
$87.5 \le x < 100$	4.5	4	4	-15	+15
$75 \le x < 87.5$	4	3	3	-20	+20
$62.5 \le x < 75$	3.5	2	2	-25	+25
$50 \le x < 62.5$	3	1	1	-30	+30
$37.5 \le x < 50$	2.5	1	1	-35	+35
$25 \le x < 37.5$	2	1	1	-40	+40
$12.5 \le x < 25$	1.5	1	1	-45	+45
$0 \le x < 12.5$	1	1	1	-50	+50

requires expert knowledge (i.e. Table 3.2.4) (in the example: $\alpha = 1$; $\beta = 1$; A = -0.4 times the value of the data point or -40; and B = 0.4 times the value of the data point or 40).

$$x = \left(\frac{\sum \text{Quality Scores} - \sum \text{Minimum Quality Scores}}{\sum \text{Maximum Quality Scores} - \sum \text{Minimum Quality Scores}} \right) x\, 100\,\%$$

Equation 3.2.7

The second method (Meier (1997)) uses data, process, and system level indicators, including indicators for assumptions, valuation, and impact category considerations. Development of conversion factors for this method relies on previous experience using the method and in other data quality analysis. For example, the conversions in Table 3.2.5 are for the geographical correlation indicator. In this case, calculation of the additional data uncertainty for the chosen indicators uses the additional uncertainties shown in Table 3.2.5, and is characterised by a normal distribution with standard deviation of 1/4 of this range. For the example data above, (2,2,3,2,1), the additional uncertainty will equal the sum of that for each indicator: ±(10+10+20+10+5)%, or ± 55 %. Using the mean value of our example, 100, then the variation is ± 55, and the standard deviation is (45 - (-55))/4 or 27.5.

Despite the mathematical nature of these methods, the results are still subjective, reliant on expert judgement to determine the variation caused by each indicator score

Table 3.2.5: Table to obtain the additional uncertainty from I for the geographical correlation indicator for use in the data quality indicator method of Meier (Berg *et al.* (1999)).

Quality Score (I)	Additional Uncertainty Range (±%)
1	5
2	10
3	20
4	30
5	50

(Weidema (1998)). As they provide a single range for each impact category, they may enhance perception of the credibility of the LCA study results (Huijbregts (1998)). However, as knowledge of the bases of the conversion methods are limited among practitioners and decision makers alike (Huijbregts (1998)), a combined confidence result may unintentionally reduce understanding of the uncertainty.

3.2.3.7.5 Methods for Comparing System Quality Scores

Presentation of quality analysis results is in general by box plot (see Figure 3.2.3) (Coulon et al. (1997)). The basis for the choice of cut-off probabilities for the boxes (by the decision-maker) (Coulon et al. (1997)) is allowable risk, i.e. 95 % (it is true 95 out of every 100 possible cases). These plots may prove helpful, when there is minimal overlap, as in cases A and B. However, when there is substantial overlap, as in cases B and C, it is more difficult to determine which is the better option.

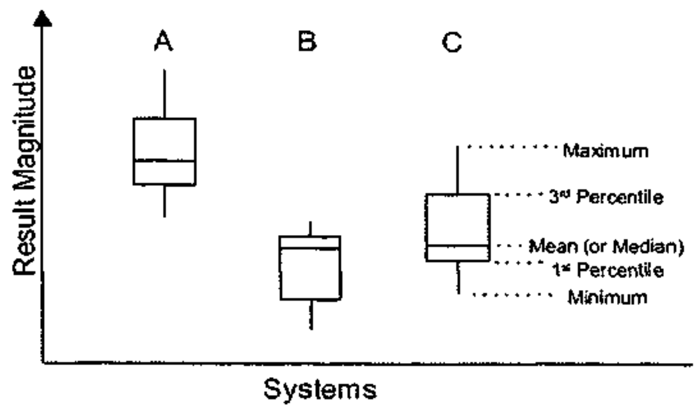

Figure 3.2.. Box plots of system quality scores for notional 'life-cycle' systems A, B and C. The basis for the positioning of the 1st and 3rd percentiles is the required confidence.

The usual method of resolving this difficulty is to perform the LCA on the difference between the cases (i.e. Case A minus Case B). If the generated quality box plot is entirely above zero, then Case A is definitely greater than Case B. When the value straddles zero, deciding between the options involves a value judgement. Generally, the basis for this judgement is the positions of mean (or perhaps the median) values, and the qualitative or quantitative reporting of the degree of crossover.

Another proposed method involves the generation of a normalised difference probability distribution (Coulon et al. (1997)), characterised as the ratio (Result $_{(\text{Case A})}$ – Result $_{(\text{Case B})}$)/Result $_{(\text{Case A})}$. If this ratio is positive (i.e. 0.12) then Case A is better than Case B by the magnitude of the ratio (i.e. 12 %). Conversely, if the ratio is negative, then Case B is better than Case A, again by the magnitude of the ratio. It is also proposed (Coulon et al. (1997)) that preparing a graph of the cumulative distribution function of this ratio (see Figure 3.2.4), using a Monte-Carlo simulation, will allow the estimation of the probability of one case being significantly better than the other (say by a 10 % margin). For example, in Figure 3.2.4 there is a 50 % probability that Case B is better than Case A by at least 10 %, while there is only a 20 % chance that Case A is better than Case B by the same margin. This step is essential only if closer inspection of the system cannot separate the alternatives.

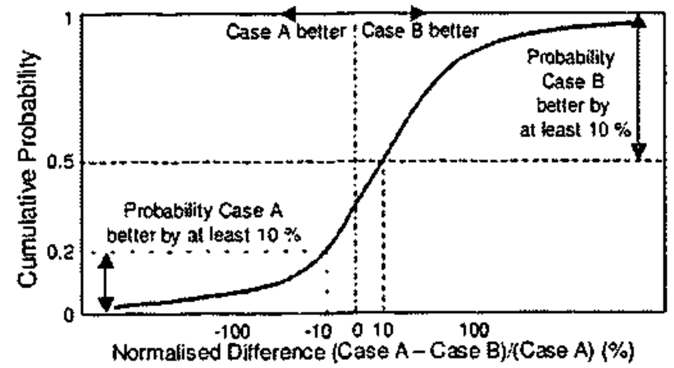

Figure 3.2.4: An example of a comparison between notional 'life-cycle' systems A and B using the cumulative normalised difference method.

3.2.3.7.6 Current Practice

Data quality analysis is not current practice in LCA studies (2, 3, 4). A recent survey of LCA studies reported that only 4 out of 30 studies explicitly reported problems of uncertainty, and of these only one produced a quantitative analysis and two produced a qualitative analysis (Ross *et al.* (2002)). However, this situation is an improvement from an earlier study of data quality and databases (Vigon and Jensen (1995)), which reported no use of uncertainty analysis. Similarly, out of approximately 30 reports examined for the review in Section 2.4 (Chapter 2) only one report used a quantitative quality analysis technique (confidential report). Another used a simplified quantitative method on a process level (BHP Minerals Technology (2001)), and one gave a qualitative discussion of uncertainty (Audus (1996)). Additionally, a few others gave indicative ranges based on the variability of one data value (i.e. AGA (2000), Rogner and Khan (1998)).

This practice may reflect the already considerable time requirements for many LCAs and a belief that detailed quality analysis does not provide sufficient benefit to decision makers to justify its expense. Others have suggested that the current unsatisfactory state of data quality analysis, and its lack of transparency, (Guinée *et al.* (2001)) provide little incentive to include it in LCA studies. Thus, research into possible simplifications is important to reduce the need for detailed analysis of each datum (Huijbregts (1998)), and the time required for data quality analysis (Maurice *et al.* (2000)). Integration of data quality methods into existing LCA software programs could reduce time requirements (Huijbregts *et al.* (2001)).

3.2.3.8 General Difficulties When Applying LCA

There are many difficulties encountered in LCA studies, due mainly to its lack of maturity as an environmental analysis tool (Huppes (1996), Udo de Haes (1993), Burgess and Brennan (2001)). This is despite the process of standardisation, which has laid the framework for LCA, without defining the appropriate methodology (ISO 14040). Causes include the lack of universally applicable methods (for all possible studies), and a need for further development overall (Huppes (1996)). The lack of universal methodology will not change, since no method could cover all possible cases (Guinée *et al.* (2001), Udo de Haes *et al.* (1999), Burgess and Brennan (2001)). In addition, it would reduce the ability of practitioners to adapt the methodology to suit their system (Guinée *et al.* (2001), Burgess and Brennan (2001), ISO 14040), or for technological changes (ISO 14040) and thus possibly the applicability of their results for further analysis. As ISO 14040 states, there is no single method for LCA studies; studies should suit the requirements of the user and study.

Common difficulties encountered throughout LCA are decisions not amenable to purely scientific analysis. The bases for such decisions are moral values, professional judgement, or legislative requirements. There are two classes of these judgements, assumptions and value choices (ISO 14042). Assumptions are technical choices that could be validated if data were available (i.e. the background levels of a particular substance), whereas value choices are based on political, ethical or ideological principles (i.e. weighting human health against rain forest destruction) (Udo de Haes *et al.* (1999)). These principles change with time and place, in a similar way to the concept of sustainability (see Section 2.2.3, Chapter 2). Yet, it is not possible to completely separate an LCA from value choices, because the aim of LCA is to support such decisions (Huppes (1996)). Therefore, the documenting of all decisions based on values will allow others to understand the results in context and establish for themselves the validity of the applied value choices.

3.2.4 Summary of Methods for Producing Environmental Indicators

The method presented here, life cycle assessment (LCA), can produce the required indicators of environmental sustainability for a sustainability assessment of electricity generation systems. LCA applies the 'life-cycle' perspective and gives results in the form of indicators. However, the LCA method has a number of limitations requiring further investigation.

3.3 METHODS FOR PRODUCING ECONOMIC INDICATORS

3.3.1 Overview of Methods for Producing Economic Indicators

Chapter 2 identifies wealth generation, and capital requirements as the most important economic indicators of sustainability for electricity generation. Thus, this section, examines methods for the calculation of these indicators.

Sections 3.3.2 and 3.3.3 examine the two commonly encountered methods for developing economic indicators: value added (VA) and net present value (NPV) methods. A limitation of VA methods, highlighted in Section 3.3.2, is that they do not account for capital expenditure. Section 3.3.4 examines a simplified method of combining VA and an estimate of capital expenditure.

3.3.2 VALUE ADDED

Value added (VA) has been suggested as an indicator of economic sustainability. Value added is the difference in value between what is sold and the non-labour, non-capital inputs that are purchased for its production, i.e. goods, materials and services (Azapagic and Perdan (2000), IChemE (2002a), Richards (1998)) (see Equation 3.3.1).

$$VA = S - P$$

Equation 3.3.1

where: VA = value added; S = sales revenue; and P = cost of purchased materials, energy and services.

In this definition, P does not include materials in nature (Wood (1978)). Thus, for coal mining, coal in the ground has no cost. P includes changes in stocks of materials (Wood (1978)). Added value indicates the available cash fund from which labour, company profits, shareholder dividends and any capital investment must come (Gilchrist (1971), Riadhi-Belkaoui (1999)), and is indicative of the wealth generated by the efforts of the owners and employees (Riadhi-Belkaoui (1999)).

For a 'life cycle' perspective system, value added, is the sum of the value added by each subsystem within the system boundary (see Equation 3.3.2) (Azapagic and Perdan (2000)).

$$VA = \sum_{l=1}^{L}\sum_{s=1}^{S}\left[S_{s,l} - \left(R_{s,l} + MES_{s,l}\right)\right]$$

Equation 3.3.2

where: $S_{s,l}$ = sales from stage s in year l (AUD 1999); $R_{s,l}$ = cost of raw materials used in stage s in year l (AUD 1999); $MES_{s,l}$ = cost of materials, energy and services purchased for stage s in year l (AUD 1999); L = life of main asset (i.e. power station) (years); and S = stages in system.

In the terminology of this report:

$$VA = \sum_{l=1}^{L}\sum_{s=1}^{S}\left\{S_{s,l} - \left[\left(O\&M_{s,l} + F_{s,l}\right) - L_{s,l}\right]\right\}$$

Equation 3.3.3

where: O & $M_{s,l}$ = operating costs; $F_{s,l}$ = cost of materials produced upstream; and $L_{s,l}$ = costs of labour.

Some suggested that VA would encourage greater cooperation between workers, investors, and government, and distribute the responsibility for economic performance between all parties (Riadhi-Belkaoui (1999)). It may also be utilised to indicate the net output of a company (Riadhi-Belkaoui (1999)). The sum of VA from all sources within a nation is equivalent to its gross domestic product (GDP), which is widely reported. Thus, VA enables calculation of the contribution to GDP (Riadhi-Belkaoui (1999) Azapagic and Perdan (2000), IChemE (2002a)). Moreover, VA is the basis for many taxation schemes (i.e. value added taxation or VAT) and so is readily obtainable (Azapagic and Perdan (2000)).

Some have questioned the ability and accuracy of VA to be measure of economic value. A similar measure to VA, economic value added (EVA), which includes a capital expenditure term, has been widely applied by industries (Azapagic and Perdan (2000)), indicating widespread belief that calculation of VA should include the costs of capital investment. While VA excludes the costs of labour for the study subject, it still includes some labour costs. VA accounts for material, energy and service purchases; the price paid for these purchases includes an allowance for the labour costs of the seller. Further, high VA does not necessarily indicate high economic performance, as judged using other indicators of wealth (Riadhi-Belkaoui (1999), Richards (1998)). Thus, it may lead to poor management decisions, which increase VA, but reduce other indicators of wealth (Riadhi-Belkaoui (1999)).

Others have suggested, instead, that successful capital investment indicates high economic performance (Richards (1998)). Consequently indicators of this success, i.e. profitability, internal rates of return (IRR) and net present values (NPV), were more able to indicate the generation of value (Richards (1998)), and thus progress towards sustainability. VA was one of a number of short cuts to these more rigorous calculations (Richards (1998)). Consequently, the presentation of other economic indicators, with VA, is necessary to adequately indicate economic performance towards sustainability (Azapagic and Perdan (2000)).

While one set of sustainability indicators (IChemE (2002a)) uses VA as the preferred unit of product or service value, another (Global Reporting Initiative (2002)) regards VA as a descriptor of the scale of a company (or industry), rather than an indicator of sustainable development. Both of these sets present other economic indicators, such as sales; cost of goods, materials, and services; cost of labour; research and development; and capital costs. Thus, VA requires the presentation of other economic indicators to adequately indicate economic impacts. Therefore, it may be better to use a different economic measure as an indicator of the wealth generation aspect of economic sustainability.

3.3.3 NET PRESENT VALUE AND INTERNAL RATE OF RETURN METHODS

3.3.3.1 OVERVIEW OF NET PRESENT VALUE AND INTERNAL RATE OF RETURN METHODS

An important conclusion of Section 3.3.2 was that the Value Added indicator is inadequate to completely describe economic sustainability, due to its failure to account for all economic costs. Net present value (NPV) and internal rate of return (IRR) methods do not suffer this disadvantage. Therefore, this section examines these methods to assess their suitability as descriptors of economic performance.

Section 3.3.3.2 defines NPV and IRR. Sections 3.3.3.3 to 3.3.3.5 then present the methods to calculate the cost information necessary for a NPV or IRR calculation. Section 3.3.3.3 discusses the costs necessary to construct the facility (capital costs). Section 3.3.3.4 discusses the costs necessary to operate and maintain the constructed facility (operating costs). Section 3.3.3.5 discusses the combined cost burden due to capital and operating costs.

3.3.3.2 NET PRESENT VALUE AND INTERNAL RATE OF RETURN

Net present value (NPV) is the sum of the annual discounted[††††††] positive (income) and

[††††††] Discounting the cash flows takes account of the changes in the value of money over time. The general discounting formula is:

negative (costs) cash flows for the life of a project (Holland *et al.* (1974)). Positive cash flows for most product systems will include sales of the product, but may include sales of other items, such as wastes or equipment. Negative cash flows include: purchases of materials, energy and services; capital investment; maintenance; insurance; taxes; and other expenses. The sustainability assessment of Leca *et al.* (2002) (see Section 2.4.3.2, Chapter 2) uses NPV as an indicator. For the electricity generation systems, positive cash flows consist of electricity revenue alone[‡‡‡‡‡‡]. If the basis of comparisons between systems is the sale of a common amount of electricity, then each system will have identical positive cash flow. Therefore, with such a basis, differences in the NPV of the electricity generation systems will be due to the negative cash flows. Equation 3.3.4 shows how to calculate these negative cash flows, assuming that taxes have no great influence.

$$NPC = \sum_{y=1}^{Y} O\&M_y + I_y$$

Equation 3.3.4

where: NPC = net present cost (sum of negative cash flows); $O\&M_y$ = operating costs for year y; I = capital investment costs for year y; and Y = total number of years of operation (life).

This NPC includes two types of costs: those attributable to the operation and maintenance of existing plant (O & M) and those attributable to construction of new plant (C_R). Sections 3.3.3.3 (C_R) and 3.3.3.4 (O & M) describe methods for estimating these costs. Then, Section 3.3.3.5, describes methods for the combination of these parts to produce the NPC indicator.

$$PV = FV/(1-i)^n$$

where: PV = present value; FV = future value; *i* = real inflation rate; and n = number of years between FV and PV.

[‡‡‡‡‡‡] Some systems may sell wastes (i.e. some black coal systems sell ash produced from coal combustion).

3.3.3.3 Capital Costs

Capital costs (C_R) are the sum of all costs required to produce a working system. C_R thus includes land, planning and construction (fixed capital cost), commissioning and working capital costs. The choice of method for estimation of capital cost depends on the desired accuracy, and resources (time and money) available (Brennan (1990), Holland *et al.* (1974)). The most basic of estimates involve the use of factors to estimate the variation in plant capital costs with sales revenue or production capacity (Holland *et al.* (1974)). More advanced estimates require detailed designs of equipment and entire plants which contribute significantly to the overall system cost (Holland *et al.* (1974)). Detailed estimates require a detailed design of the entire system (Holland *et al.* (1974)). In this case, the electricity generation systems have 'life cycle' boundaries, which include several complex plants and transport systems. Resources are not available for detailed estimations of these entire systems. Consequently, adopted is the basic estimation approach.

Basic approaches assume that the cost of any system is a function of its size or sales revenue. The most common approach uses production capacity as the indicator of relative cost (Holland *et al.* (1974), see Equation 3.3.5). For chemical processing plants the exponent (ψ) is often 0.7, but a wide range of exponents is possible.

$$I_2 = I_1\left(\frac{Q_2}{Q_1}\right)^{\psi}$$

Equation 3.3.5

where: I_1 and I_2 = capital costs of system 1 and 2 respectively; Q_1 and Q_2 = production capacity of systems 1 and 2 respectively; and ψ = exponent of the estimate.

When comparing many plants, Equation 3.3.5 can be simplified to Equation 3.3.6.

$$I = A(Q)^{\psi}$$

Equation 3.3.6

where: I = capital costs of similar systems; Q = production capacities of similar systems; ψ = the exponent for this type of system; and A = correlation constant.

Obtaining exponents for each system requires correlation of capital costs (I) and

production capacities (Q) for existing, similar systems, using Equation 3.3.6. Many studies, reports, and other sources report I and Q information.

Collection of capital costs for each subsystem occurs independently, as capital costs for entire systems are unlikely to be available. Thus, each subsystem requires its own correlation and exponent. Estimates of the required production capacity in each subsystem, corresponding to the system production capacity, allow the estimation of each subsystem's contribution to the system capital cost. For example, to produce one MWh of electricity might require the production of 1 tonne of coal from a coal mine. Summing the subsystem contributions provides the system capital cost (see Equation 3.3.7).

$$I = \sum_{s=1}^{S_T}\left[A_s(Q_s)^{\psi_s}\right]$$

Equation 3.3.7

where: I = system capital cost estimate; Q_s = production capacity for subsystem s to obtain the system output; ψ_s = exponent for subsystem s; A_s = correlation constant for subsystem s; and S_T = total number of subsystems.

Economic estimates of electricity generation systems commonly report annualised costs (AC), rather than NPC (for examples, see Section 2.4.3.4, Chapter 2). NPC discounts the costs of a project over its life (Figure 3.3.1). AC also discounts project costs, but modifies the discounted amounts so that they are all the same value (Figure 3.3.1). Using the AC method will enable verification against previous estimates. For the AC method annualised capital costs (C_R) replaces I_y in Equation 3.3.4. Estimating C_R requires the use of the standard annuity present worth equation (Equation 3.3.8) (from Holland (1974)).

$$C_R = \frac{I.i}{\left[1-\frac{1}{(1+i)^n}\right]}$$

Equation 3.3.8

where: C_R = annual capital costs; I = system capital cost estimate; i = cost of capital;

and n = life of loan.

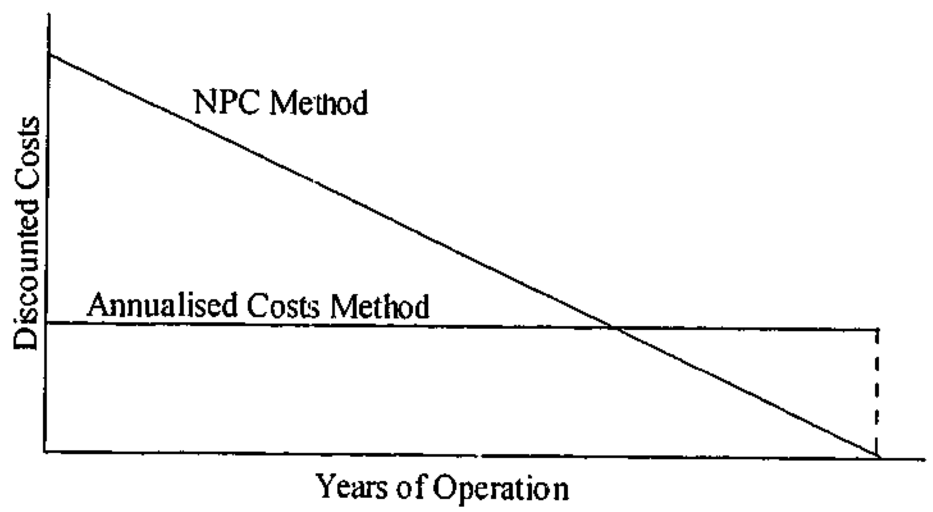

Figure 3.3.1: Comparison of the discounted costs profiles from the net present costs (NPC) and annualised costs (AC) methods.

Provision of capital is from two sources: equity and debt. Equity are owned funds, such as earnings from previous years or other activities, funds from share issuing, and any other moneys (Holland *et al.* (1974)). Debt are funds borrowed from others. Each source has an inherently different rate of interest. The interest rate for equity is the rate if invested in other systems, while for debt is the rate required by the lender (Middleton (1977)). The effective interest rate is the sum of the products of interest applying to a capital source and the proportion of capital obtained from that source[§§§§§§]. This effective interest rate is the cost of capital (*i*).

Each of the subsystems may have a different life (n), and thus estimation of n is not simple. For example, the economic life of power station might be 30 years, while that of a coal mine might be only 15 years. Thus, for the power station to operate for its economic life, it requires a replacement coal mine after 15 years. The costs associated in construction and operation, and the technologies employed in this second mine, will probably be different to the original (Brigham and Ehrhardt (2002)). Thus, a method for aggregating these discontinuous costs is required.

§§§§§§ For example (adapted from Middleton (1977)):

Source	Proportion	Rate (%)	Weighted Rate (%)
Debt	0.3	6	1.8
Equity	0.7	12	8.4
Total	1.0		10.2

There are two methods to consider projects with unequal lives: the replacement chain (common life), and equivalent annual annuity approach (Brigham and Ehrhardt (2002)). Of these, the replacement chain approach was most commonly used, as it can be calculated using spreadsheet programs (Brigham and Ehrhardt (2002)), and can apply to cases where the costs associated with the replacement projects vary from the initial project (Clark *et al.* (1989)). This method obtains equal lives by adding replacement projects to the end of the initial project. For example, a one project (A) has a life of 4 years, but project B has a life of just 2 years. To obtain an equivalent life for project B, a replacement project B of 2 years life is added to the end of the original project B. Thus, it can be assumed that two project Bs are necessary for every project A, and the system capital cost will be the sum of A's and the two B's capital costs. Thus, multiplying each subsystem's capital cost (Equation 3.3.7) by a term representing its equivalent life (λ_s) can account for the effects of non-equivalent lives (see Equation 3.3.9).

$$I = \sum_{s=1}^{S_T}\left[\lambda_s A_s (Q_s)^{\psi_s}\right]$$

Equation 3.3.9

where: I, Q_s, ψ_s, A_s and S_T as in Equation 3.3.7; and λ_s = equivalent life of subsystem s.

Now Equation 3.3.8, using I values from Equation 3.3.9, can estimate the annual capital repayment (C_R) for a system with any number of subsystems.

3.3.3.4 OPERATING COSTS

Operating costs (O & M) include all operating costs, except costs related to the repayment of capital, such as interest and load payments. For example, the operating costs of a fossil fuel power station include: fuels, auxiliary fuels, water, chemicals and other materials, operating, administration and management labour, maintenance materials and labour, contracted services (including sewerage and waste disposal) and automobile fuels. These operating costs exclude taxes. Similarly to capital costs, estimating operating (O & M) can use detailed or simple methods. Detailed methods attempt to obtain real or characteristic values of each individual type of cost for each type of system, while simple methods use factors appropriate for each type of industry (Brennan (1990)). As with capital costs, resources are not available to apply the detailed methods, and this assessment uses the factored approach. There are published factored operating cost estimation techniques for some types of subsystems (see Brennan (1990) for some data and sources).

Similarly to capital costs, obtaining exponents for each subsystem requires correlation of O & M costs (O & M) and some production parameter (P) for existing, similar systems, using the simplified basic approach (see Equation 3.3.10). Many studies, reports, and other sources report O & M and P information. This estimate includes both fixed and variable operating costs, as reports of operating costs normally do not present each of these costs contributors separately.

$$O\&M = B(P)^{\omega}$$

Equation 3.3.10

where: O & M = operating costs of similar systems; P = production of similar systems; ω = the exponent for this type of system; and B = correlation constant.

Subsystems, within the system boundary, provide a proportion of their materials, energy and services to other subsystems. For example, a coal mine provides a power station's fuel, both of which are subsystems within the 'life cycle' boundary. Thus, the costs of coal provision must count once only, when estimating the O & M costs of the entire system.

$$O\&M = \sum_{s=1}^{S_T} O\&M_s - F_{other,s}$$

Equation 3.3.11

where: O & M and O & M_s = operating and maintenance costs for the system and subsystem s respectively; $F_{other,s}$ = costs for provision of materials, energy and services from other subsystems; and S_T = total subsystems.

For the annualised costs (AC) method (see Section 3.3.3.3), annualised operating costs (O & M) replaces O & M_y in Equation 3.3.4. Annualised operating costs is the real dollar value of O & M for each year during the study subject's operating life. Thus,

the O & M cost collection should collect O & M costs in real dollars. Therefore, O & M_y in Equation 3.3.4 is equal to O & M.

3.3.3.5 Annualised Costs

Equation 3.3.4 shows the net present costs (NPC) for each subsystem. For the annualised costs (AC) method, C_R and O & M replace I_y and O & M_y (Equation 3.3.12).

$$AC = O\&M + C_R$$

Equation 3.3.12

where: AC = annualised costs; O & M = operating costs; and C_R = annualised capital costs.

3.3.3.6 Summary of Net Present Value and Internal Rate of Return Methods

The methods presented here can produce indicators of generated wealth and capital requirements for a sustainability assessment of electricity generation systems. These methods can overcome the difficulties inherent in VA. However, AC represents NPV only because of the assumption that positive cash flows (i.e. sold electricity) do not vary between electricity generation systems.

3.3.4 Adding Capital to Value Added

One of the stated exclusions of the value added (VA) measure was capital expenditure. One method for adding capital to VA is economic value added (EVA). EVA is the net operating profit (after tax) minus a capital charge. The capital charge is the capital repaid (i.e. amortised capital charge) times the required rate of return applying for that company (i.e. internal rate of return) (Stern *et al.* (2001)) (see Equation 3.3.13). The amortised capital charge is determined using sinking fund depreciation, and thus annual capital payments are constant (Stern *et al.* (2001)). Research and development, advertising and promotions, and employee training are included as a capital charge (Stern *et al.* (2001)).

$$EVA = \sum_{l=1}^{n}\sum_{s=1}^{S}\left[NOPAT_{s,l} - \left(C_{s,l}.CA_{s,l}\right)\right]$$

Equation 3.3.13

where: $NOPAT_{s,l}$ = net operating profit before interest but after tax from subsystem s in year l (AUD 1999); $C_{s,l}$ = cost of capital for subsystem s in year l (%); $CA_{s,l}$ = capital expended by subsystem s in year l; n = life of system (years); and S_T = subsystems in system*******.

EVA proponents claim it to estimate the true economic profit and the creation of shareholder value, better than any other existing measure, and be easily measurable and understandable (Azapagic and Perdan (2000)). Yet, it has also been criticised as too simplistic, misrepresenting the true financial situation, and containing subjective assumptions (Azapagic and Perdan (2000)). EVA calculates over a single year period, and thus is dependent on annual capital investment decisions (Azapagic and Perdan (2000)). Thus, reducing capital expenditure in a year, and increasing it in others, enables manipulation of EVA, for example to influence share prices for personal gain. Some assumptions made during the calculation also distort EVA, such as the distribution of research and development capital (Azapagic and Perdan (2000)). Such flaws have led to the development of similar, alternative measures (Azapagic and Perdan (2000)). Some claim that the cause of many of these difficulties is the use of different techniques to estimate the capital charge for EVA (Richards (1998)).

Subtracting the annualised capital repayment (C_R) (Equation 3.3.8) from VA (Equation 3.3.2) produces an analogous indicator to EVA (Equation 3.3.14). This indicator, given the name capital inclusive value added (CVA), will approximate an EVA indicator, but without many of its flaws. For example, the C_R value is an average capital expenditure over many years, and manipulation on a yearly basis is difficult.

$$CVA = VA - C_R$$

Equation 3.3.14

where: CVA = capital inclusive value added; VA = value added; and C_R = annualised

******* This equation is from Azapagic and Perdan (2000).

capital costs.

3.3.5 Summary of Methods for Producing Economic Indicators

The methods presented here can produce the required indicators of economic sustainability for a sustainability assessment of electricity generation systems. It examined several methods for producing the wealth generation indicator: value added (VA), annualised costs (AC), and capital value added (CVA); and a capital requirements indicator (I).

The VA method is an incomplete indicator as it neglects the effects of capital costs on wealth generation. The AC and CVA methods include capital costs and thus overcome this difficulty. Thus, a comparison of the VA and AC and CVA indicators may establish if the inclusion of capital costs is essential to indicate wealth generation.

3.4 METHODS FOR PRODUCING SOCIAL INDICATORS

3.4.1 Overview of Methods for Producing Social Indicators

Chapter 2 identified employment, and health and safety as the most important social indicators of sustainability for electricity generation. Thus, this section, examines methods for the calculation of these indicators.

Section 3.4.2 examines methods for developing the employment indicator. Section 3.4.3 examines methods for developing the health and safety indicator.

3.4.2 Employment

The total employment due to the activities of one system is difficult to estimate. Direct employment in the system is the sum of the employees actively working in each subsystem (see Equation 3.4.1).

$$ED = \sum_{s=1}^{S_T} ED_s$$

Equation 3.4.1

where: ED and ED_s = direct employment in the system and subsystem s respectively; and S_T = subsystems in system.

The actual employment generated by the system will be greater than the direct employment. The total employment generated will include temporary staff, employment associated with purchased materials and services, and employment generated through the spending of direct employees. Estimation of this indirect employment uses employment multipliers, produced from input output tables (ABS (2001)). Generation of these multipliers assumes linear relationships between output and employment, and the outputs of different industries (ABS (1994)). For example, if an industry (A) increases its output (by say 100 %), demand for outputs from other industries (including B) will also increase (by say 50 %). These multipliers assume that output and employment in these industries will increase linearly to match that demand (i.e. B's output and employment would increase by 50 %). Different types of multipliers exist, depending on the amount of additional employment they include. The types of multipliers of most interest are:

- Type 1A multipliers include all additional employment caused by the employment of one person in that industry from other industries whose output is required for that industry.

- Type 1B multipliers include Type 1A employment. It also includes the additional employment required for all industries that provides outputs for the other industries (of Type 1A indicators) and for these industries, and so on. It includes all additional employment in all industries caused by the employment of one person in the subject industry.

- Type 2A multipliers include Type 1B employment and employment caused through the spending of the employees included in the Type 1B multiplier. This indicator includes the original increase of one person.

- Type 2B multipliers are Type 2A multipliers minus the original increase of one person. Thus, 2B represents the industry wide additional increase in employment when employing one person in an industry.

Estimation of indirect employment first requires classification of direct employment into industry, using the classifications provided with the multipliers (ABS (2001)). Application of the multiplier appropriate for that industry (EM) converts the classified direct employment into indirect employment. The sum of these indirect employees is the total indirect employment (Equation 3.4.2).

$$EI = \sum_{s=1}^{S_T}\sum_{c=1}^{C_T} EM_c \, x \, ED_{s,c}$$

Equation 3.4.2

where: EI = indirect employment for the system, EM_c = employment multiplier for industry classification c, $ED_{s,c}$ = direct employment in industry classification c in subsystem s; S_T = subsystems in system, and C_T = total industry classifications.

3.4.3 Employee Health and Safety

The most common safety indicators for industries are lost time injuries (LTI) and fatalities. LTI are illnesses and injuries, which cause an absence of at least one day. Many companies report the number of LTI or a LTI frequency (LTIF, LTI per million work hours) as part of their Operational Health and Safety schemes. Equation 3.4.3 shows how to convert from LTIF to LTI.

$$LTIF = LTI \, x \, ED \, x \, WP$$

Equation 3.4.3

where: ED = direct employment; and WP = worker productivity (work hours per direct employee).

Equation 3.4.4 and Equation 3.4.5 show how to produce the system LTI and fatalities indicators.

$$LTI = \sum_{s=1}^{S_T} LTI_s$$

Equation 3.4.4

$$\text{Fatal} = \sum_{s=1}^{S_T} \text{Fatal}_s$$

Equation 3.4.5

where: LTI and LTI_s = LTI for the system and subsystem s respectively; Fatal and $Fatal_s$ = fatalities for the system and subsystem s respectively; and S_T = the total number of subsystems.

LTI and fatalities indicators include immediate health impacts, such as illness and diseases that occur during work, but fail to recognise those that occur later in life. The LTI indicator is an imperfect indicator of safety as it neglects injuries that result in absences of less than one day. It is thus possible for a task to cause innumerable small injuries, without contributing the LTI indicator. They also neglect such injuries to non-employees. The toxicity indicator of environmental sustainability will account for some LTIs and fatalities, caused by material emissions, but neglect injuries to non-employees from transport vehicle accidents. Thus, they are low estimates of the ultimate health and safety impact of systems.

3.4.4 Summary of Methods for Producing Social Indicators

The methods presented here can produce the required indicators of social sustainability for a sustainability assessment of electricity generation systems. Examined are methods for producing employment indicators (ED and EI), and health and safety indicators (LTI and Fatal).

3.5 PRODUCING INDICATORS OF SUSTAINABILITY WITH A 'LIFE-CYCLE' PERSPECTIVE

Of the indicator methods, only the LCA method (Section 3.2.3) was developed to have boundaries with a 'life-cycle' perspective. Thus, for the economic and social indicators to have 'life-cycle' boundaries a number of modifications to their methods are

necessary. This section examines whether the components that allow the LCA method to produce indicators with this perspective may apply to the economic and social indicators of sustainability ~~(economic and social)~~.

Allocation distributes the environmental impact causing materials between the individual products of a subsystem (see Section 3.2.3.4). If the studied system has subsystems with multiple products, it will be necessary to allocate all types of impact (environmental, economic and social) between the products. It may be necessary when allocating economic and social impacts to use a different basis than for environmental impacts.

Sensitivity analysis estimates the influence of key decisions, such as the choice of allocation methods, on the indicators, by showing the outcome from each probable choice (see Section 3.2.3.6). Detailed economic assessments often use this type of analysis to test the influence of uncertain parameters in their models, such as future interest rates and inflation. Estimation of the influence of decisions, such as the choice of basis for allocation, on the indicators of sustainability will help to prove their robustness. Therefore, sensitivity analysis will be of benefit for all types of indicators.

Uncertainty analysis estimates the influence of data uncertainties on the indicators (see Sections 3.2.3.6 and 3.2.3.7). Detailed economic assessments sometimes use this type of analysis to test the influence of uncertainties in base data. Uncertainties are present in all types of data, and thus uncertainty assessment is valid for all types of indicators of sustainability. However, there is no standardised method for uncertainty assessment of systems with a 'life-cycle' perspective, and thus application of uncertainty analysis for this case is limited to the environmental indicators.

Normalisation is an optional step in LCA, which divides each of the study subject's indicators by a corresponding indicator for an entire region (i.e. the world or Australia) (see Section 3.2.3.5). This aids in understanding the relative importance and magnitude of the indicators produced by an LCA (Guinée *et al.* (2001)). Normalisation may thus allow a similar understanding of relative importance and magnitude between all types of indicators of sustainability.

3.6 SUMMARY OF METHODS FOR PRODUCING SUSTAINABILITY INDICATORS

Methods shown here can produce values for each of the indicators listed in Chapter 2. Table 3.6.1 shows the methods selected to obtain values for the indicators listed in Table 2.5.1 (Chapter 2).

While the environmental method (LCA) assesses impacts using the 'life-cycle' perspective, equivalent methods are not available for economic and social indicators. Therefore, the assessment will compare several economic and social indicator methods for each indicator. The use of some of elements of the LCA method may aid the adaptation of the economic and social indicator methods to the 'life-cycle' perspective. Of these, the allocation procedure allows distribution of impacts from subsystems if they have multiple products. Other elements, such as the uncertainty and sensitivity analyses, allow consistent reporting of the indicators robustness to assumptions and data uncertainties. Lastly, the normalisation procedure enhances understanding of the relative importance and magnitude of the indicators.

Consensus is still lacking in several areas of application of the LCA method. The most glaring examples are the lack of accepted methods for characterising the impact of resource depletion and for uncertainty analysis. Therefore, it would seem that some examination of the effect of these problems on the environmental indicators is necessary to ensure wide acceptance of the conclusions from this study.

Table 3.6.1: List of equations necessary to estimate each of the indicators of sustainability. The indicators are from Table 2.5.1 (Chapter 2). Column A contains the abbreviations for each impact.

Name		A	Equations	
Environmental Indicators				
Resource Depletion	CML method	RD	Equation 3.2.1	Equation 3.2.4 & Equation 3.2.5
	Energy depletion	EN	Equation 3.2.2	
	Exergy destruction	EX	Equation 3.2.2	
Climate Change		CC	Equation 3.2.4 & Equation 3.2.5	
Acidification		AD		
Eutrophication		EU		
Photochemical Smog		PS		
Human Toxicity		HT		
Eco-Toxicity		ET		
Solid Waste		SW		
Particulates		PM		
Water Consumption		WD		
Economic Indicators				
Wealth Generation	Value Added	VA	Equation 3.3.3	
	Annualised Cost	AC	Equation 3.3.12	
	Capital Inclusive VA	CVA	Equation 3.3.14	
Capital Requirements	Capital	I	Equation 3.3.9	
	Annualised Capital	C_R	Equation 3.3.8	
Social Indicators				
Employees	Direct	ED	Equation 3.4.1	
	Indirect	EI	Equation 3.4.2	
Health and Safety	Lost Time Injuries	LTI	Equation 3.4.3 & Equation 3.4.4	
	Fatalities	F	Equation 3.4.5	

4. ELECTRICITY GENERATION SYSTEMS AND DATA

'Access to electricity services has proven to enhance economic development and social welfare. For example, electrification of rural areas in developing countries contributes to a better distribution of employment opportunities and a more equitable access to health and education services, as well as improving the overall standard of living.'

INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA) (2000), PG. 9.

4.1 OVERVIEW OF ELECTRICITY GENERATION SYSTEMS AND DATA

The previous two chapters developed a methodology and practical methods for sustainability assessment using a set of indicators. These practical methods require detailed information about the system to which they are applied. The methods for producing environmental indicators require information about material and energy consumption and emissions. The methods for economic indicators require information about the costs of construction and operation. Finally, the methods for social indicators require information about the number of employees and rates of injuries and illnesses. This chapter details this information for Australian electricity generation systems.

Section 3.2.3.4 (Chapter 3) establishes that a methodology for data collection is necessary for a life cycle assessment (LCA) before data collection. LCA is the method proposed for the production of the environmental indicators of sustainability. Section 4.2 provides details of this methodology for data collection and a justification for using a similar methodology for the economic and social indicators. Section 4.3 describes some important, operating electricity generation systems which consume Australian fossil fuel, as well as some proposed alternatives. Additionally, Section 4.3 details the collected data and operations necessary to produce a whole-of-system data set and sustainability indicators for each electricity generation system. During data collection, it is often necessary to make choices and assumptions in the presence of uncertainty. Similarly, it is often necessary to use data where there is a degree of uncertainty as to its accuracy. Section 4.4, details how to apply the uncertainty and sensitivity analyses to estimate the affect of such uncertainties on the sustainability indicators.

4.2 *METHODOLOGY FOR DATA COLLECTION*

4.2.1 OVERVIEW OF METHODOLOGY FOR DATA COLLECTION

Utilisation of the methods for obtaining sustainability indicators, described in Chapter 3, requires the collection of various data from the electricity generation systems. Data from these systems may vary with employed technology and operational experience. Furthermore, data collection may employ different techniques, i.e. direct measurement (once only or continuous), simulation, or estimation. Consequently, data from each source will have its own inherent accuracy.

ISO 14041 recommends, for an LCA, documentation of the methodology used for data collection. This will increase ~~other's~~ confidence in the conclusions, by ensuring transparency of data inclusion and rejection decisions and assisting duplication the results of the study (ISO 14041). These aims are equally important to the economic and social indicators. Thus, a defined methodology for data collection should exist before data collection begins.

Section 4.2.2 establishes and explains the methodology for data collection. An important decision in data collection is the scope, or system boundary. Section 4.2.3 discusses appropriate system boundaries for the electricity generation systems.

4.2.2 METHODOLOGY FOR DATA COLLECTION

Two procedures are central to data collection: criteria for inclusion; and accuracy requirements. The included data should be relevant to the scope of the assessment: electricity generation systems consuming Australian black coal, brown coal and natural gas. Consequently, the accuracy of data from systems within the scope is greater than

data from without. Use of data from outside the scope is restricted to occasions where data from within the scope is lacking. Where multiple sources for data exist within the scope, the average has been adopted is ~~preferred~~. The reference unit for data will be the major output. For example, in coal mining the major output is the mass-rate of coal mined per annum, whereas in electricity generation it is the rate of electricity production per annum.

The accuracy of data should be marked to allow for assessment of the accuracy of the generated sustainability indicator values. Section 3.2.3.6 and Section 3.2.3.7 (Chapter 3) discusses methods for estimating the sensitivity and accuracy of environmental indicators. These methods require pedigree matrix scores (see Table 3.2.3, Chapter 3) and range data (average, minimum and maximum values). These features are also common to economic and social data. Thus, collection of these features for economic and social data will enable the use of these methods for these indicator types. Balances of mass (for environmental indicators), cashflow (economic) and employment (social) ensure consistency with the laws of conservation.

4.2.3 SYSTEM BOUNDARIES FOR DATA COLLECTION

Chapter 2 acknowledges that sustainability assessment requires the use of the 'life-cycle' perspective. Consequently, a fossil fuel electricity generation system, viewed using this perspective, will include all processes from the extraction of the fossil fuel from the ground to the use of the generated electricity (Figure 4.2.1). The 'life cycle' perspective requires that the system should obtain all the materials it consumes, directly from the environment. Thus, a full 'life-cycle' system would include all of the boxes in Figure 4.2.1.

Data for the box labelled 'Materials and Other Fuel Production', which includes the production systems for materials (such as, parts, chemicals and drinking water) and other fuels (such as, petrol), is not available yet for Australian systems and resources for their collection are insufficient to obtain accurate estimations. Thus, the assessment ignores impacts caused by this box.

Detailed investigations (Spath *et al.* (1999), IAEA (2000), BHP Minerals Technology (2001), Gorokhov *et al.* (2002)) have shown that the contribution from the 'Construction and Commissioning' and 'Decommissioning and Rehabilitation' boxes for electricity generation systems, when averaged over the life of the plant (at least 30

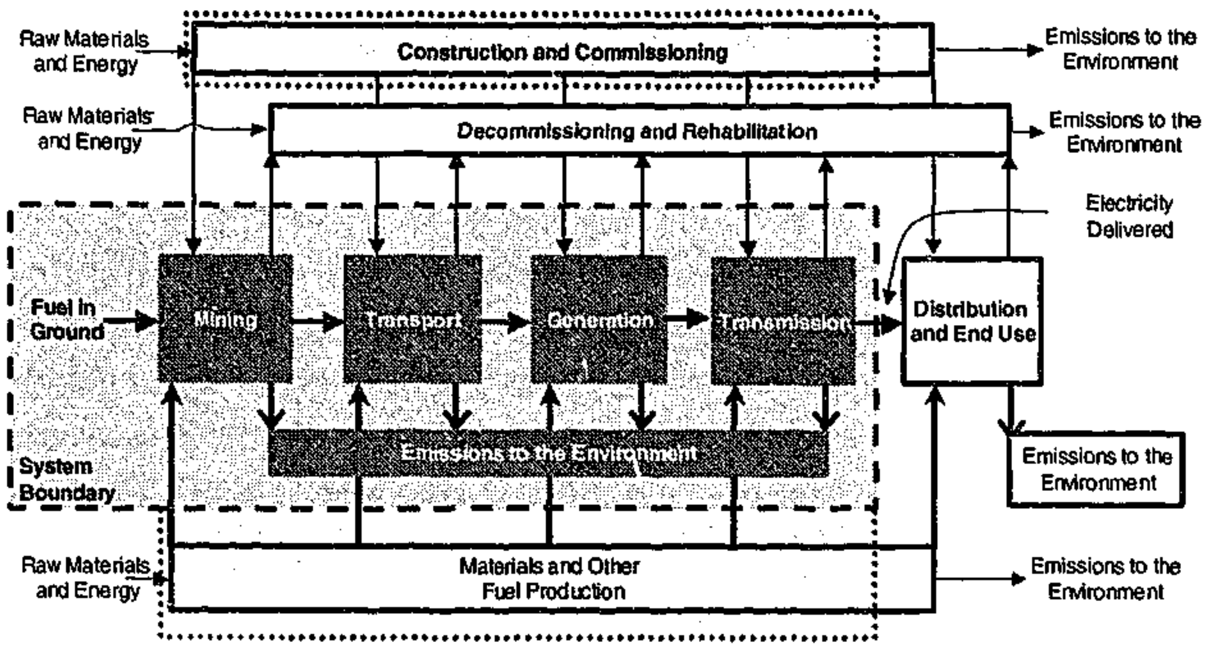

Figure 4.2.1: Diagram of an electricity generation system for consuming fossil fuels, with 'life-cycle' boundaries. Also shown is the simplified perspective (grey = all impacts, spotted = economic impacts only).

years), are minor in comparison with operational impacts*. During the short construction period (2-4 years), these impacts may be important. However, the assessment ignores environmental and social impacts caused by this box.

The assessment includes economic impacts from 'Construction and Commissioning' in the capital requirements indicator (I, see Section 3.3.3.3, Chapter 3) and from 'Material and Other Fuel Production' in the wealth generation indicators (AC, VA and NPC, see Sections 3.3.2, 3.3.3.5 and 3.3.4, Chapter 3)†.

Electricity delivery involves high-voltage transmission over cables, conversion to a lower voltage in a substation, and distribution to consumers over more cables. Once delivered, consumers are free to use the electricity as they like. Voltage reduction, distribution and end use are highly differentiated and location specific. Consequently, they are hard to quantify as single measures. The features of these systems are insensitive to the source of the electricity they transport and consume, and thus to the choice of electricity generation technology. Therefore, the impacts they produce will be

* One study found that by including the greenhouse gas emissions of the manufacture of equipment used in the upstream processes, which is necessarily greater for oil and natural gas than for coal, reduced the differences between the climate change impact oil and gas systems (Ogawa and Yoon (1998)).

† The included economic impact of consuming materials and other fuels is the purchase price.

identical for all cases and not influence the relative impacts between different systems. The transmission subsystem thus excludes the 'Distribution and End-Use' box.

Figure 4.2.1 shows this simplified perspective, bounded by the system boundary. This simplified perspective is similar to that of the FENCH technique (see Section 2.4.3.2, Chapter 2).

Within the simplified perspective's system boundary, Figure 4.2.1 shows four subsystems: fuel mining; fuel transport; electricity generation; and electricity transmission. These subsystems represent physical separations, often divisions between company ownership, and are present for each fossil fuel. They are thus convenient subdivisions (subsystems) for each sub system's description.

4.2.4 SUMMARY OF METHODOLOGY FOR DATA COLLECTION

These procedures allow the development of a consistent and accurate data set for use in producing sustainability indicators.

4.3 ELECTRICITY GENERATION SYSTEMS AND DATA

4.3.1 OVERVIEW OF ELECTRICITY GENERATION SYSTEMS AND DATA

Australia uses many different types of systems for generating electricity from fossil fuels. This section presents a simple description of these systems, and an estimation of their prevalence in Australia. The sustainability assessment method requires information (data) about the impact, on the environment, economy and social welfare, of each of these systems. Rules and limitations are placed on data collection for the reasons given in Section 4.2. This section describes the data collected, indicates its source, and details the manipulations necessary to produce sustainability indicators.

Sections 4.3.2 to 4.3.4 describe and show the collected data for the electricity generation systems: Section 4.3.2 for systems consuming either domestic or export black coal; Section 4.3.3 for systems consuming brown coal; and Section 4.3.4 for systems consuming natural gas or LNG. Information sources comprise public reports of corporations, research organisations, industry organisations, national and state government departments (mainly Australian but including some from other nations, notably the U.S.A. and U.K.), and other sources, such as computational process models. Additional data sources include contact with personnel from research, industry, and government organisations. Appendix 1 provides tables of the sources for each data value. A lack of sufficient data in some areas has forced the omission of some data. While Sections 4.3.2 to 4.3.4 report some minor omissions, Section 4.3.5 details omissions relevant to all sections. Each section contains four subsections, which independently detail each subsystems data collection. This data is presented using that subsystem's output as a basis, e.g. coal mining data is presented per mass of coal mined. The sustainability assessment aims to produce indicators of sustainability for the system, and thus needs data with the system's output as a basis, e.g. coal mined per MWh of electricity delivered. Section 4.3.6 presents conversions and other similar data manipulations necessary to produce system indicator scores.

4.3.2 DOMESTIC AND EXPORT BLACK COAL

4.3.2.1 MINING SUBSYSTEM

4.3.2.1.1 Description of the Mining Subsystem

Black coal occurs naturally in many locations within Australia. It normally occurs in sub surface layers. Often multiple layers of coal will occur at the same site, interspersed with other mineral matter. Finding these layers involves geological and mining engineering studies, both airborne and surface, and finally sampling (Blackham (1993)).

Mining is the extraction of black coal from these layers. Mining in Australia uses both underground and open cut methods. In NSW, approximately 60 % of coal is from open-cut mines, with the remainder from underground mines (Lowe (2000)). In Queensland, nearly 90 % of coal is from open cut mines (Department of Mines and Energy (2000)).

There are three types of open cut mines: strip mining, open pits and highwall. Strip mining is the progressive mining of a coal layer, with overburden from above the layer dumped behind the extracted coal (Figure 4.3.1, top). Open pits have multiple benches, do not use draglines, and dump overburden distant from the mining operation (in or outside the mine). Overburden removal is by blasting and removal of spoil piles by draglines (strip) or shovels and dump trucks (open cut) (Aspinall *et al.* (1993), Kukla *et al.* (1993)). Coal removal is by drilling and blasting (seams greater than 2 m thick), direct digging or ripping, using shovels, excavators and front end loaders (Kukla *et al.* (1993)). Coal transport to the mine's stockpile is by haulers or conveying systems. Highwall mining is the horizontal cutting of coal unobtainable by conventional open cut methods. It is not widely used in Australia.

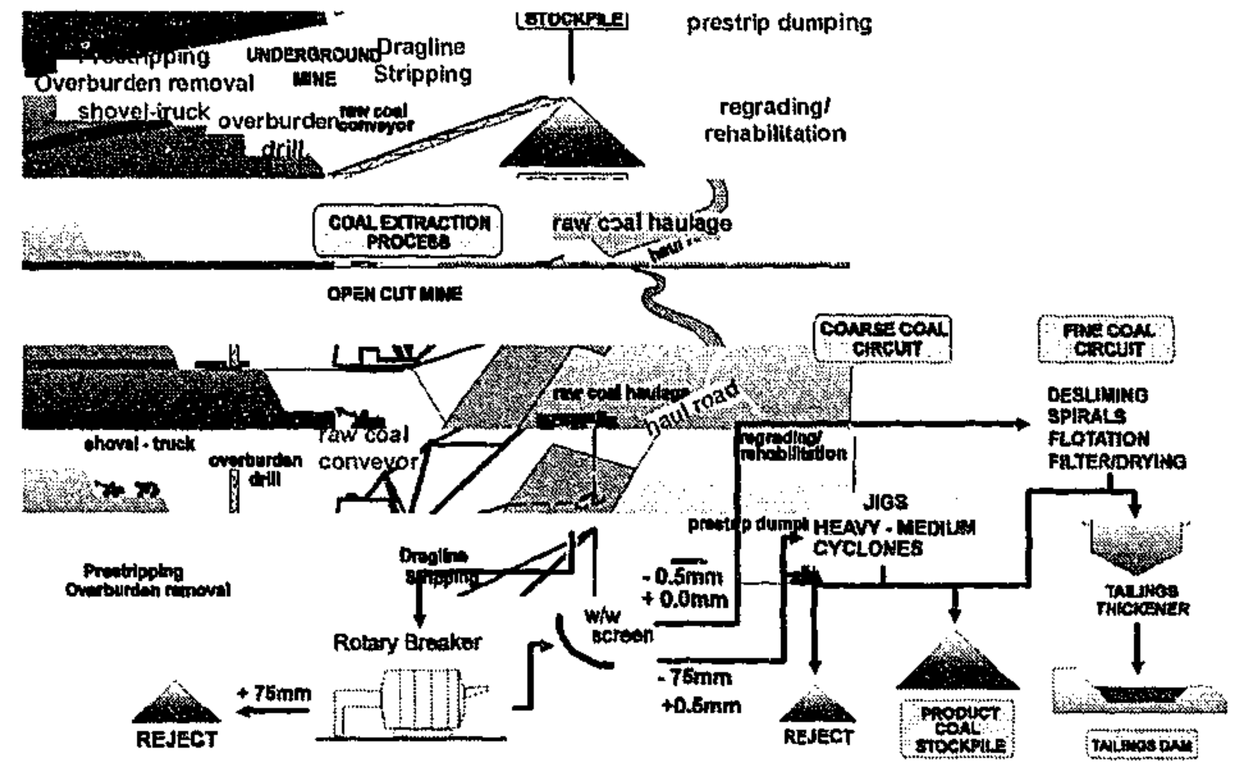

Figure 4.3.1: Steps in the mining of black coal (adapted from NGGIC (1998b)).

There are two main methods of underground mining: Bord and Pillar, and Longwall (Hedley and McDonald (1993)). Both methods have relatively minor impacts on the surface. Bord and Pillar methods break the coal seam into regular sections. Pillars of coal support the roof material while expanding the mine. Often extraction of these pillars occurs after mining of the section is complete. Longwall mines create very large pillars (longwalls) for extraction. This method often produces coal at a faster rate than Bord and Pillar methods. In both cases, transport of coal is by conveying belt systems, which may include shuttle cars (only for some underground mines) and trucks. Ventilation is highly important in underground mining as most coal seams contain carbon dioxide (CO_2) and methane (CH_4) gases. CO_2 gas can cause suffocation. Methane, or even coal dust, can cause fire or explosion in air.

In all cases, coal is stored, in open stockpiles (for large quantities) or bins (for small quantities (up to 6 kt)), before transportation. This enables smoothing of production rates, which reduces the costs of conveying the coal. To ease its transport, crushing of coal may occur at various points.

In both surface and underground mining, the water table may need lowering (by extracting water from below the mine), to ensure the safety of mining and minimise the chance of flooding. Rehabilitation of surface areas to pre-mine condition is a requirement for all mines. It must restore the productivity, ecological integrity, and economic and aesthetic value of the land (Chadwick *et al.* (1987)).

Black coal production in Australia has, unlike brown coal, two markets; domestic and export. Australia exports more coal than it consumes domestically (around 60 %), which is in sharp contrast to most other countries (Doherty (1993)). Thus, Australian coal producers must be able meet both domestic and export economic and quality demands. Mineral matter reduces the thermal value of coal as it reacts in high temperatures to form ash. Reduction of mineral matter is often by gravity separation techniques, which separate the heavy ash from the light coal. The heavy ash material is around 15 % of the raw coal for underground mines and 25 % for open cut mines (Joint Coal Board (2000)).

Infrastructure for the 'average mine' in this assessment consists of four sets of mining equipment; two each for underground and surface mining. The exact machinery used will depend on the amount of coal produced from each set. In underground mining, the two methods used are Bord and Pillar and Longwall, and for surface mining the two methods are truck and shovel and dragline. Other equipment, necessary for all methods, includes crushing equipment, stockpile spreading, maintenance and reclaiming equipment, transport loader(s), mine water extraction and conveyance equipment, and service and maintenance areas.

4.3.2.1.2 Material Flows

4.3.2.1.2.1 Assumptions

Data in this section refers to black coal mines in New South Wales and Queensland only, since it is in these states that most of Australia's black coal production occurs. It includes only those mines producing coal for the domestic power production industry. The average coal mine produces 2686 kt of coal per annum, of which 1166 kt is for domestic consumption (the remainder is for export) and 24.7 % of total coal production

is from underground mines (Data Ref. C1).

While the data excludes material flows due to construction and final rehabilitation (see Section 4.2.3), it includes rehabilitation during normal operation.

4.3.2.1.2.2 Material Requirements

Table 4.3.1 shows the materials used in an average black coal mine. Water (low quality) includes water extracted from subterranean aquifers, as well as from surface sources. This analysis omits a number of minor inputs, for example, chemicals, maintenance materials and lubricating oils for machinery, due to a lack of data.

Table 4.3.1: Material requirements for the mining of 1 Mt of coal from an average black coal mine.

Material	GWh	Ref.
Electricity	19.7	C2
	kg	Ref.
Coal	1.00×10^9	Basis
Diesel	1.50×10^6	C3
Petrol	1140	C4
Explosives (Ammonium Nitrate)	1.50×10^6	C5
Limestone	4.01×10^6	C6
Overburden	6.50×10^9	C7
Water (high quality)	45.6	C8
Water (low quality)	7.97×10^8	C9

4.3.2.1.2.3 Material Emissions

Table 4.3.2 shows the emissions from an average black coal mine. Mining of overburden allows access to the black coal. However, as mining this overburden is a moving process, rather than a substantial modification, the solid waste value does not include overburden. The methane and carbon dioxide emissions values include emissions, which naturally occur when coal is exposed to air. Emissions from the oxidation of waste coal are not included due to a lack of verified data. Dust emissions due to blasting, movement and transport are negligible in comparison with that caused by coal transport. Thus, the conservative dust emissions estimate in Section 4.3.2.2 will

Table 4.3.2: Material emissions from the mining of 1 Mt of coal from an average black coal mine.

Material	kg	Ref.
Black Coal	1.00×10^9	Basis
Overburden	6.50×10^9	C10
Water (low quality)	1.21×10^8	C11
Carbon dioxide	4.71×10^6	C12
Methane	3.52×10^6	C13
NMVOC	7290	C14
N_2O	135	C15
NO_x	6.79×10^4	C16
CO	2.63×10^4	C17
SO_2	1.38×10^4	C18
Particulates	2800	C19

include mining emissions.

4.3.2.1.3 Economic Flows‡

Table 4.3.3 shows the capital costs, I, of open cuts (Equation 4.3.1) and underground mines (Equation 4.3.2) with yearly production capacity, Q. The average mine, which produces 24.7 % of its coal underground, has a capital cost as shown in Equation 4.3.3 (Data Ref. C1).

Table 4.3.3: Correlation parameters for the capital costs of black coal mining.

Equation	A	ψ	Range I ($ million (AUD 2000))	Range Q (Mtpa)	Data Ref
Equation 4.3.1	158	0.690	50.4 - 1080	0.3 - 15	B1
Equation 4.3.2	107	0.616	46.6 - 271	1 - 4	A1

$$I = 130(Q)^{0.690} + 90.0(Q)^{0.616}$$

Equation 4.3.3

for: Q = 1 to 4 Mtpa and I = $ 50.4 to 271 million (AUD 2000).

Table 4.3.4 shows the operating costs, O & M, of open cuts (Equation 4.3.4) and underground mines (Equation 4.3.5) with yearly production, P. Thus, the average mine, which produces 24.7 % of its coal underground, has an operating cost as shown in

‡ See Sections 3.3.3.3 and 3.3.3.4, Chapter 3 for explanation of I, O & M, Q, P, A, B, ψ and ω.

Equation 4.3.6 (Data Ref. C2). Of these operating costs, some 16 % is due to washing, and thus domestic coal, which is generally unwashed, has an operating cost 84 % of the value determined by the correlation.

Table 4.3.4: Correlation parameters for the operating costs of black coal mining.

Equation	B	ω	Range O & M ($ million (AUD 2000) per annum)	Range Q (Mtpa)	Data Ref
Equation 4.3.4	24.9	0.966	0.116 - 277	0.00386 - 12.1	B2
Equation 4.3.5	45.1	0.969	0.196 - 215	0.00354 - 5	A2

$$O\&M = 19.0(P)^{0.966} + 34.3(P)^{0.969}$$

Equation 4.3.6

for: P = 0.00386 to 5 Mtpa and O & M = $ 0.246 to 253 million (AUD 2000) per annum.

4.3.2.1.4 Social Flows

Table 4.3.5 shows the social flows in average black coal mining. LTIF for black coal mines is 26 LTI per 10^6 WH and WH per employee is 2237.

Table 4.3.5: Employment, LTI and fatalities data for an average black coal mine.

Parameter	Value per Mt	Ref.
Employment	85	C1
LTI	9.7	C2
Fatalities	0.015	C3

4.3.2.2 Transport Subsystem

4.3.2.2.1 Description of the Transport Subsystem

Transport of coal for use in domestic power stations can be by conveyors, trucks or trains. For long distance transport over land, railways are the most common form of transport. Railway cars have a normal capacity of 75 tonne, and trains of up to 45 cars are becoming common (Horrocks and Gadsden (1993)). Over short distances, transport is by either fleets of trucks or conveyor systems. Trucks most often use dedicated roads, but in some cases, smaller trucks operate on public roads. Conveyor systems rely on long term supply agreements between mines and power stations.

Transport of coal for export is by rail, then bulk sea freighter, and finally rail to the power station stockpile. Trucks or coastal barges transport a small amount to ports in NSW from nearby mines. Port facilities can stockpile up to 2.50 Mt, load up to 10500 tonne/hr, and have annual capacities of up to 28 Mt of coal. Sea transport is by ships of up to 250000 DWT (dead weight tonnes). Japan, South Korea, and Taiwan consume most of Australia's export black coal, but many other countries consume smaller amounts.

Power stations stockpile coal to ensure the feed to the power station is continuous.

These transport systems have loading stations for each type of vehicle, vehicles, pathways (rails, roads, or conveyor), and transfer and unloading stations.

4.3.2.2.2 Material Flows

4.3.2.2.2.1 Assumptions

The important assumptions in black coal transport are those of distance and the capacity of vehicles. Table 4.3.6 and Table 4.3.7 shows these assumptions for domestic and for export coal respectively. All transport which occurs within the mine boundary is not considered in this analysis, neither is transport associated with the power station.

4.3.2.2.2.2 Material Requirements

Table 4.3.8 shows the materials used in average black coal transport. Diesel consumption in the road and rail transport of coal is dependent on weight, and thus they will consume less fuel when returning to the mine for a new cargo. The calculation assumes that the vehicle only operates between the mine and power station, and always has a full load or is empty. The mining and generation subsystems include water consumption for domestic black coal transport[§]. This analysis omits a number of minor inputs, for example, chemicals, maintenance materials and lubricating oils for machinery, due to a lack of data.

[§] Water consuming activities, such as vehicle washing and dust suppression, usually occur at transfer points located at the mine and power station.

Table 4.3.6: Transport distances and vehicle capacities for domestically consumed black coal.

Transport Method	Distance (km)	Ref.	Vehicle Capacity (t)	Ref.	% of coal transported	Ref.
Road	10	X1	23 (28)	X2	15.5	X3
Rail	209	X4	5400 (7200)	X5	22.4	X6
Conveyor	5.1	X7	NA		62.1	X8

Table 4.3.7: Transport distances and vehicle capacities for black coal exported to Japan (Ass. = assumed value, Diff. = by difference).

Transport Method	Distance (km)	Ref.	Vehicle Capacity (t)	Ref.	% of coal transported	Ref.
Road	2	Ass.	23 (28)	X2	11.5	Diff.
Rail (Domestic)	209	X9	5400 (7200)	X5	88.5	X10
Ocean	8100	X11			100	
Rail (Foreign)	50	Ass.	5400 (7200)	X5	100	

Table 4.3.8: Material requirements for the transport of 1 Mt of coal from an average black coal mine to an average power station.

Material	Domestic		Export	
	GWh	Ref.	GWh	Ref.
Electricity	0.508	A1	5.33	B1
	kg	Ref.	kg	Ref.
Coal	1.00×10^9	Basis	1.48×10^9	B2
Diesel	7.27×10^5	A2	3.81×10^6	B3
Fuel Oil			1.44×10^7	B4
Water (low quality)			2.51×10^8	B5

4.3.2.2.2.3 Material Emissions

Table 4.3.9 shows the material emissions from average black coal transport. Dust emissions are included with particulates from combustion of fossil fuels. Due to a lack of data, it is assumed that 50 % of the black coal lost in transport is lost as dust, and the remainder as solid waste. The wastewater value assumes that no water is lost.

4.3.2.2.3 Economic Flows

Table 4.3.10 shows the capital costs, I, of rail (Equation 4.3.7), road (Equation 4.3.8) and conveyor (Equation 4.3.9) transport, with yearly production capacity, L.Q.

Table 4.3.9: Material emissions from the transport of 1 Mt of coal from an average black coal mine to an average black coal power station.

Material	Domestic		Export	
	kg	Ref.	kg	Ref.
Coal	9.98×10^8	A3	1.00×10^9	Basis
Solid waste	1.10×10^5	A4	4.73×10^8	B6
Wastewater			2.51×10^8	B7
Carbon dioxide	2.27×10^6	A5	5.47×10^7	B8
Methane	186	A6	4590	B9
NMVOC	3520	A7	5.06×10^4	B10
N_2O	65.3	A8	3290	B11
NO_x	3.28×10^4	A9	9.62×10^5	B12
CO	1.27×10^4	A10	1.74×10^5	B13
SO_2	6660	A11	8.91×10^5	B14
Particulates	1.12×10^5	A12	1.17×10^6	B15

Equation 4.3.10 (ports) and Equation 4.3.11 (shipping) show the capital costs of sea transport (Data Ref. A4). The combined capital costs are factored estimates using the proportions in Table 4.3.6 and Table 4.3.7, and Equation 4.3.12 for domestic and Equation 4.3.13 for export black coal transport.

Table 4.3.10: Correlation parameters for the capital costs of black coal transport.

Equation	A	ψ	Range		Data Ref
			I ($ million (AUD 2000))	L.Q (km.Mtpa)	
Equation 4.3.7	2.52	0.806	181 - 3900	200 to 9019	A1
Equation 4.3.8	1.21	0.680	0.763 - 22.3	0.511 - 73	A2
Equation 4.3.9	1.91	0.889	1.06 - 673	0.511 - 730	A3

$$I = 33.7(Q)^{0.881}$$

Equation 4.3.10

for: Q = 0.8 to 22.6 Mtpa and I = $ 27.7 to 525 million (AUD 2000).

$$I = 1.46 + 0.0036\,(L.Q)$$

Equation 4.3.11

for: L.Q = 10327 to 21243 km.Mtpa and I = $ 39.7 to 78.9 million (AUD 2000).

$$I = 0.339\,(L_{Road}.Q)^{0.680} + 0.755\,(L_{Rail}.Q)^{0.806} + 1.26\,(L_{Conv}.Q)^{0.889}$$

Equation 4.3.12

$$I = 0.276\,(L_{Road}.Q)^{0.680} + 2.29\,(L_{Rail\,1}.Q)^{0.806} + 1.46 + 0.0036\,(L_{Ocean}.Q) + 44.9(Q)^{0.881} + 2.52\,(L_{Rail\,2}.Q)^{0.806}$$

Equation 4.3.13

Table 4.3.11 shows the operating costs, O & M, of rail (Equation 4.3.14), road (Equation 4.3.15), conveyor (Equation 4.3.16) and sea (Equation 4.3.17) transport, with yearly production, L.Q. The combined operating costs are factored estimates; Equation 4.3.18 for domestic and Equation 4.3.19 for export black coal transport.

Table 4.3.11: Correlation parameters for the operating costs of black coal mining.

Equation	B	ω	Range		Data Ref
			O & M ($ million (AUD 2000) per annum)	L.P (km.Mtpa)	
Equation 4.3.14	1.64	0.621	44.0 - 2200	200 - 109000	A5
Equation 4.3.15	0.182	0.796	0.107 - 5.54	0.511 - 73	A6
Equation 4.3.16	3.24	0.588	2.19 - 190	0.511 - 1010	A7
Equation 4.3.17	0.155	0.388	5.43 - 739	9580 - 21200	A8

$$O\ \&\ M = 0.0412\,(L_{Road}.P)^{0.796} + 0.647\,(L_{Rail}.P)^{0.621} + 2.45\,(L_{Conv}.P)^{0.588}$$

Equation 4.3.18

$$O\ \&\ M = 0.0325\,(L_{Road}.P)^{0.796} + 1.52\,(L_{Rail\,1}.P)^{0.621} + 0.155\,(L_{Ocean}.P)^{0.388} + 1.64\,(L_{Rail\,2}.P)^{0.621}$$

Equation 4.3.19

4.3.2.2.4 Social Flows

Table 4.3.12 shows the social flows in average black coal transport. LTIF for road transport is 22.6 LTI per 10^6 WH and WH per employee is 2255. LTIF for rail transport is 17.4 LTI per 10^6 WH and WH per employee is 1931. LTIF for ship transport is 7.8 LTI per 10^6 WH and WH per employee is 1949. This estimate excludes port employees and their LTI and fatalities.

Table 4.3.12: Employment, LTI and fatalities data for average black coal transport.

Parameter	Domestic		Export	
	Value per Mt	Ref.	Value per Mt	Ref.
Employment	27.2	A1	105	B1
LTI	1.05	A2	3.85	B2
Fatalities	0.0053	A3	0.0083	B3

4.3.2.3 GENERATION SUBSYSTEM

4.3.2.3.1 Description of the Generation Subsystem

Steam turbine systems are the most widely used technology for electricity generation from black coal (Figure 4.3.2). This technology uses steam to turn the blades of a steam turbine, and a generator converts this rotational energy into electricity.

At steam turbine plants, an amount of black coal is stored. Before consumption of the fuel, pre-heating and milling occurs. Transport of the milled fuel into the boiler is by the air needed to combust the fuel. The boiler uses a particular arrangement of fuel entry points to maximise steam generation, and minimise the amount of nitrogen in the air converted to NO_x. Water pipes form the walls of the boiler. The heat generated by

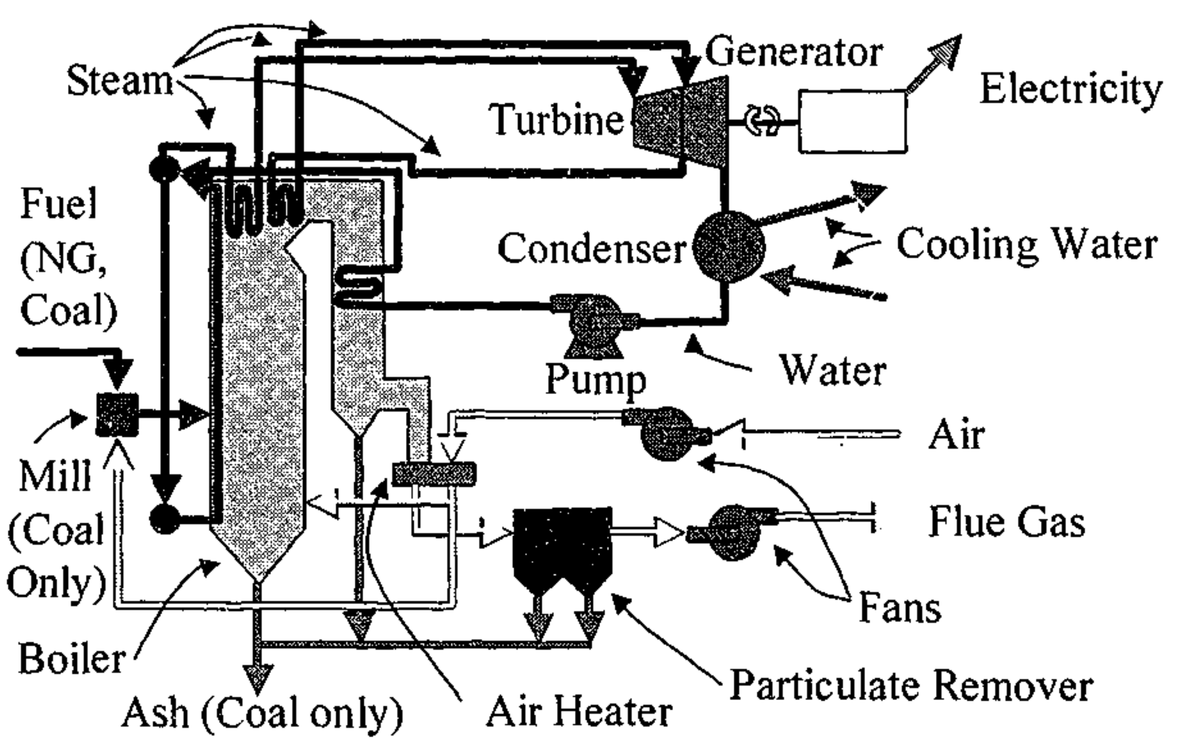

Figure 4.3.2: Simplified representation of the steam turbine electricity generation technology.

fuel combustion converts the water within the pipes to steam. Further pipes in the top of the boiler, heat the steam to higher temperatures (superheating). Superheating dramatically improves both the amount of heat extracted from the boiler and the amount of electricity generated per unit of fuel consumed. Mineral matter in the coal becomes ash on combustion. Large ash particles collect on the boiler walls and floor. Removal of ash from the floor is either continuous or periodic. Removal of ash from the walls requires the boiler to be not operating. Collection of smaller ash particles from the flue gas uses bag filters or electrostatic precipitators (Woodruff *et al.* (1998)). Some ash is sold, but most becomes landfill. Combustion converts much of the sulphur and nitrogen in the coal into SO_2 and NO_x. Control of these emissions occurs in other countries (Lavely and Ferguson (1996)), but not in Australia because of the low sulphur and nitrogen levels in Australia coals. After removal of ash particles the gas created by the fuel combustion ('flue gas') passes through a fan (used to ensure a constant flow of flue gas) and out to the environment through a stack.

The water used in the boiler and turbine must be very pure, to reduce corrosion, in the boiler and steam system and is thus heavily treated. The source of feed water for the treatment plant is municipal drinking water supplies ('high quality'). After it has left the turbine, the steam is condensed and recycled to the boiler. Two types of condenser system are prevalent in Australia: once-through and circulating. In the once-through system, water from a large reservoir (usually a lake or ocean) passes through the condenser and returns to the reservoir. In the circulating system, water circulates between the condenser and a cooling tower, where air reduces the temperature of the cooling water resulting in the evaporation of much of the water. Water from an external reservoir (often a river) replaces this evaporated water. These condenser systems use large quantities of lower-quality water.

The electricity generation industry in Australia has grown in a fragmentary manner. Until the 1990's, electricity provision was the responsibility of state governments, who developed their own state electricity supply network. This fragmentary development has ensured that most existing power stations have different designs, even though they all use the steam turbine technology. Consequently, a wide range of electricity generation efficiencies (electrical energy exported from the power station divided by the energy consumed as fuel) occurs. Age and steam conditions have important influences on the electricity generation efficiency of steam plants. Newer plant incorporates design features found to improve older plants. Higher temperature and pressure steam increases the efficiency of steam turbines, as it allows greater energy extraction at the turbine (for example, see Hunt (1991)). The maximum efficiency obtainable from steam turbine systems is in the high 30's, but the average efficiency in Australia is around 34 %.

Some proposed technologies promise to increase efficiencies above this maximum. One of the most promising technologies is the integrated gasification, combined cycle (IGCC) technology (Figure 4.3.3). In this technology, a gasifier converts the solid coal into a combustible gas by partial oxidation (CO, CH_4, H_2, plus other non-reactive gases). Removal of the sulphur and other environmental contaminants in this gas can then occur before combustion. As the volume of this combustible gas is much less than the flue gas, this removal is easier before combustion. A combined cycle system, much the same as that used for natural gas (see Figure 4.3.7), consumes the cleaned gas. These systems consist of a combustor, a gas turbine, a heat recovery steam generator (HRSG), and a steam turbine. The gas turbine uses the heat and momentum of the product gas from the combustor to turn the blades of a turbine. A generator produces electricity from the rotational energy of the turbine. The HRSG and steam turbine operate as a steam turbine system. Some plants in Europe and North America have demonstrated the IGCC technology (i.e. Buggenum (Nl.) and Pinon Pine (U.S.A.)).

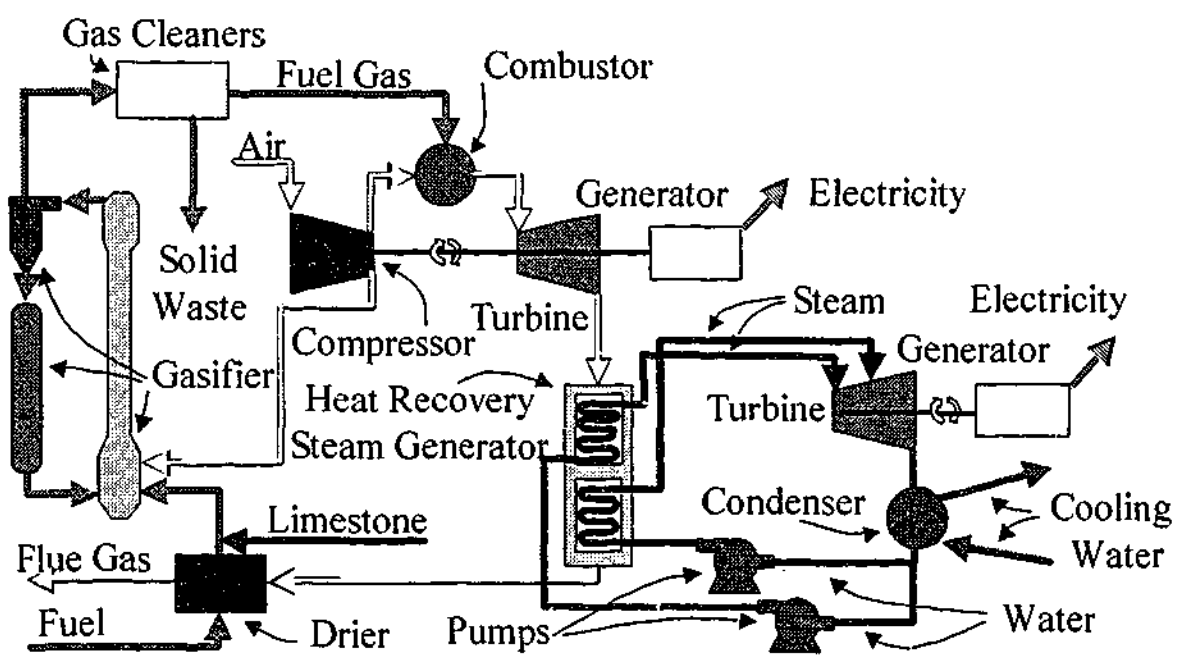

Figure 4.3.3: Simplified representation of the integrated gasification combined cycle electricity generation technology.

Many variations exist for the IGCC technology.

4.3.2.3.2 Material Flows

4.3.2.3.2.1 Assumptions

The steam turbine technology data estimates are averages of all New South Wales and Queensland black coal power stations. The basis for the IGCC technology data estimates is a report produced by the proponent (DOE (U.S.A.) (2000)). The bases for this choice are:

- the technology offers the greatest improvement in electricity generation efficiency;
- the source provides detailed design and operating information about the technology; and
- the proponent, the Department on Energy (U.S.A.), is of high standing.

The reported performance and emissions for the IGCC are verified using ProSim© process simulation software.

4.3.2.3.2.2 Material Requirements

Table 4.3.13 shows the materials used in an average power station. The auxiliary fuel is fuel oil for steam turbines, but in practice some plants use natural gas. Coke breeze and natural gas are the auxiliary fuels for the IGCC technology.

4.3.2.3.2.3 Material Emissions

Table 4.3.14 shows the material emissions from an average power station. Some power stations have begun recycling and treating all water and have zero water emissions (Delta electricity (1999)). Consumption of ash for other use is around 25 % of total ash production. Oily waste production equals oil and lubricant consumption.

4.3.2.3.3 Economic Flows

Table 4.3.15 shows the capital costs, I, of steam turbine (Equation 4.3.20) and IGCC technologies (Equation 4.3.21), with production capacity, Q. These costs assume that the IGCC technology is mature. The first IGCC system is likely to have considerably

Table 4.3.13: Material requirements for the generation of 1 net GWh of electricity from an average black coal power station.

Material	ST		IGCC	
	GWh	Ref.	GWh	Ref.
Electricity	0.0567	A1	0.0409	B1
	kg	Ref.	kg	Ref.
Coal	4.49×10^5	A2	2.52×10^5	B2
Natural Gas			7340	B3
Diesel	9.95	A3	10.6	B4
Petrol	10.9	A4	11.6	B5
Fuel Oil	302	A5		
Coke Breeze			50	B6
Limestone			3.35×10^4	B7
Sulfuric Acid	65	A6	76.8	B8
Caustic Soda	45	A7	218	B9
Ammonia	7.5	A8	2.14	B10
Chlorine	6	A9	1.71	B11
Hydrazine	0.2	A10	0.057	B12
Aluminium Sulfate (SG1.3)	1.5	A11	0.427	B13
Bromide	0.75	A12	0.214	B14
Ferriclear	0.5	A13	0.142	B15
Hydrochloric Acid	0.2	A14	0.057	B16
Antifoam	0.2	A15	0.057	B17
Lubricating Oil	1.7	A16	1.7	B18
Water (high quality)	1.97×10^5	A17	4.60×10^5	B19
Water (low quality)	1.78×10^6	A18	6.24×10^5	B20

greater costs.

Table 4.3.16 shows the operating costs, O & M, of steam turbine (Equation 4.3.22) and IGCC (Equation 4.3.23) technologies, with yearly production, P.

4.3.2.3.4 Social Flows

Table 4.3.17 shows the social flows in average black coal generation. LTIF for steam turbine technology is 7.6 LTI per 10^6 WH and WH per employee is 1373. LTIF for IGCC technology is not available, but an estimate is 17.4 LTI per 10^6 WH. An estimate of WH per employee for IGCC systems is 1931. There are no reports of fatalities in Australian black coal generation facilities. In the absence of an existing system, LTIF rates for IGCC systems are not available. As these systems hold no greater danger in

Table 4.3.14: Material emissions from the generation of 1 net GWh of electricity in an average black coal power station.

Material	ST		IGCC	
	GWh	Ref.	GWh	Ref.
Electricity	1.06	A19	1.04	B21
	kg	Ref.	kg	Ref.
Solid Waste			3.51×10^4	B22
Ash	8.41×10^4	A20	2.58×10^4	B23
Evaporation	1.51×10^6	A21	4.71×10^5	B24
Wastewater	3.39×10^5	A22	5.13×10^5	B25
Sewerage	0.0273	A23	0.0257	B26
Saline water	3.15×10^5	A24	1.01×10^5	B27
Carbon dioxide	9.83×10^5	A25	6.34×10^5	B28
Methane	9.85	A26	30.2	B29
NMVOC	18.4	A27	0.721	B30
N_2O	8.64	A28	9.15	B31
NO_x	3200	A29	156	B32
CO	119	A30	149	B33
SO_2	4010	A31	50.7	B34
Particulates	477	A32	7.18	B35

Table 4.3.15: Correlation parameters for the capital costs of black coal generation.

Equation	A	ψ	Range		Data Ref
			I ($ million (AUD 2000))	Q (MW)	
Equation 4.3.20	12.5	0.663	168 - 2410	50 - 2800	A1
Equation 4.3.21	22.7	0.615	430 - 891	467 - 1090	B1

Table 4.3.16: Correlation parameters for the operating costs of black coal generation.

Equation	B	ω	Range		Data Ref
			O & M ($ million (AUD 2000) per annum)	P (GWhpa)	
Equation 4.3.22	0.359	0.573	25.7 - 61.8	296 - 8060	A2
Equation 4.3.23	0.619	0.479	19.7 - 29.6	1373 - 9461	B2

operation, the values determined for conventional systems are equally applicable.

Table 4.3.17: Employment, LTI and fatalities data for average black coal generation.

Parameter	Domestic		Export	
	Value per GWh	Ref.	Value per GWh	Ref.
Employment	0.027	A1	0.027	B1
LTI	0.0003	A2	0.0003	B2
Fatalities	0		0	

4.3.2.4 TRANSMISSION SUBSYSTEM

4.3.2.4.1 Description of the Transmission Subsystem

Transmission occurs over high voltage cables on large transmission towers. These systems include substations, management facilities, and maintenance facilities and equipment. Kinhill Sterns (1987) details the materials necessary to construct transmission towers.

Electricity is lost during transmission, due to various factors. An important factor is distance; the greater the distance travelled by the electricity, the greater the losses. In general, black coal electricity generation systems are near major mines, and distant from major population centres. The losses attributable to transport over these distances may be significant.

4.3.2.4.2 Material Flows

4.3.2.4.2.1 Assumptions

The use of electricity from all power stations is almost exclusively in major cities, i.e. Melbourne, Sydney and Brisbane, and thus the distance over which electricity transmission takes place is the average distance between the power stations and the major capital in each state (and territory), weighted by the magnitude of electricity sent over this distance. This assessment assumes transmission loss is independent of load, varying only with transmission distance. Transmission loss is set at 0.75 % electricity loss per 100 km (Evans (1995)).

4.3.2.4.2.2 Material Requirements and Emissions

Table 4.3.18 shows the materials used in average transmission. Transmission consumes

sulphur hexafluorine (SF_6), a major greenhouse gas**, in gas-insulated substations, circuit breakers, and other switchgear (EPA (U.S.A.) (2000)). Consumption or emission data for electricity transmission systems could not be obtained††. Electricity loss estimates require yearly generation figures from power stations, estimates of distances between power stations and distribution networks, as well as estimates of interstate transfers of electricity and the transfer distance. These values allow the estimation of the average transmission distance traversed by electricity generated from black coal in Australia, 180 km. This distance, with the transmission loss assumption (see Section 4.3.2.4.2.1), can then estimate the transmission losses.

Table 4.3.18: Material requirements and emissions for the transmission of 1 GWh of electricity from an average black coal power station.

Material	GWh	Ref.	Material	GWh	Ref.
Electricity	1	Basis	Electricity	0.986	A1

4.3.2.4.3 Economic Flows

Table 4.3.19 shows the capital costs, I/L, with transmission capacity, Q (Equation 4.3.24), and operating costs, O & M, with transmission productivity, P (Equation 4.3.25) for electricity transmission.

Table 4.3.19: Correlation parameters for the capital and operating costs of electricity transmission.

Equation	A	ψ	Range		Data Ref
			I/L ($ million (AUD 2000) per km)	Q (MW)	
Equation 4.3.24	0.0109	0.636	0.338 - 1.4	250 - 4000	A1
Equation	B	ω	O & M ($ million (AUD 2000) per annum)	P (GWhpa)	Data Ref
Equation 4.3.25	0.00333	0.503	5.63 - 107	2.63 - 923	A2

** It has the greatest global warming potential (GWP) of any substance, 23 900 kg carbon dioxide (CO_2) per kg emitted (i.e. 23 900 times the effect of CO_2) (EPA (U.S.A.) (2000))

†† 74 tonnes of SF_6 was released in 1997 from all Australian industries (NGGIC (1999)).

4.3.2.4.4 Social Flows

Table 4.3.20 shows the social flows in average black coal transmission. LTIF for transmission is 5 LTI per 10^6 WH and WH per employee is 1373. Data generally refers to joint transmission and distribution companies, as there are no extant transmission only companies in Australia.

Table 4.3.20: Employment, LTI and fatalities data for average black coal transmission.

Parameter	Value per km	Ref.
Employment	0.0527	A1
LTI	0.00036	A2
Fatalities	2×10^{-5}	A3

4.3.3 BROWN COAL

4.3.3.1 *MINING SUBSYSTEM*

4.3.3.1.1 Description of the Mining Subsystem

The brown coal mines of Victoria, Australia are unique, as they are of shallow depth, high thickness, and low hardness. The coal contains a great deal of water (see Figure 4.3.4), in contrast to the lower moisture, harder black coal. There have been only six mines of commercial interest, of which five remain in operation, and four are for electricity production. Export of brown coal does not occur. Other domestic industries,

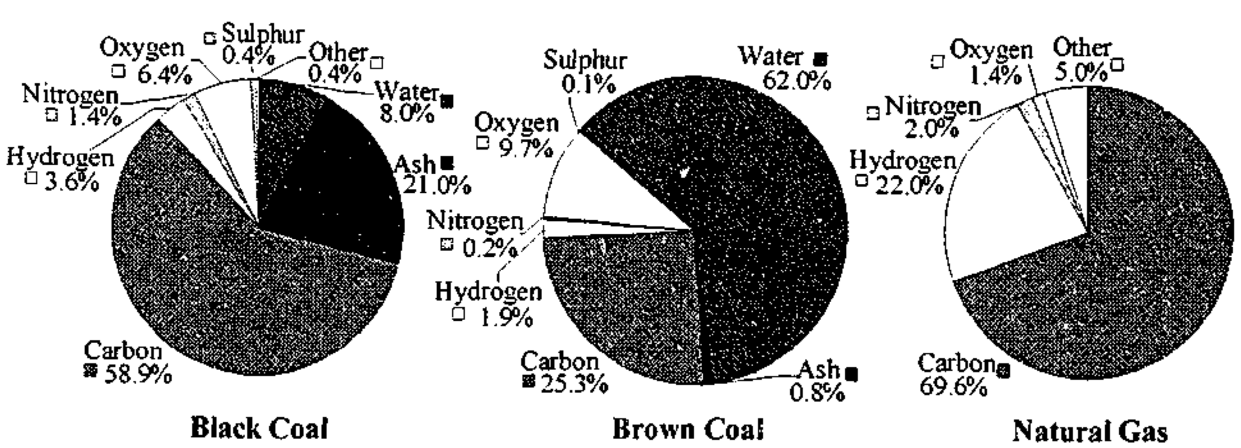

Figure 4.3.4: Representative constituents of black and brown coals and natural gas for electricity generation in Australia, highlighting the high water content of brown coals (from Brockway and Higgins (1991), NGGIC (1998a) and others).

such as briquette manufacturing, use a small amount of brown coal.

Mining of coal and overburden (waste material above the coal) is continuous, as electricity generation plants require continuous supply and storage of brown coal is difficult[‡‡]. A bunker maintains 10-16 hours of supply to ensure consistent feed. Overburden removal constitutes one level or bench, while coal extraction occurs on subsequent, lower benches (see Figure 4.3.5). Both the overburden and coal are generally soft and can be removed using coal dredgers ((Holmes (1993)). All material transport uses conveyors, as rail systems cannot handle the vast quantities of material handled[§§]. Two of the three large mines employ continuous water removal to ensure mine stability, as they operate at great depths.

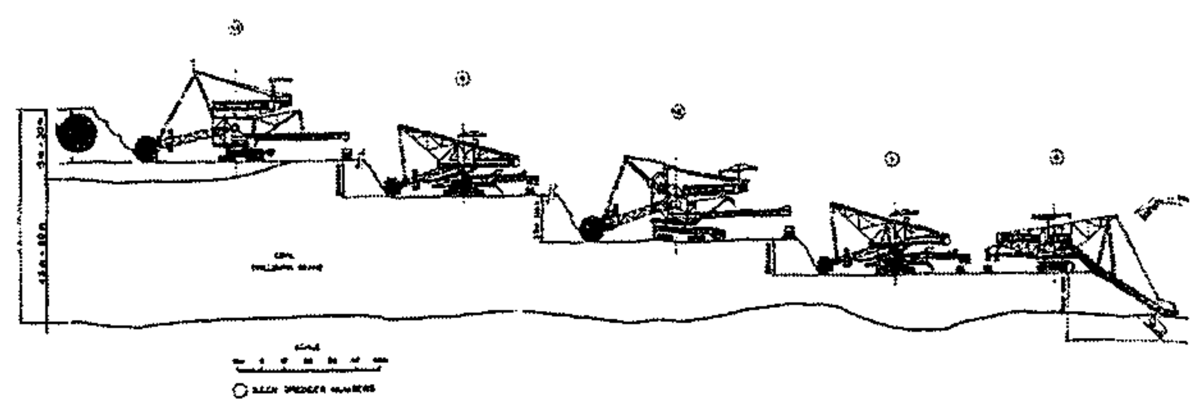

Figure 4.3.5: View of the mining face of the Yallourn brown coal mine, Victoria (Holmes (1993)). Also shows the coal dredgers used to mine brown coal.

Other infrastructure includes overburden conveyors, overburden stacker (used for spreading overburden in the overburden dump), mine water extraction and conveyance equipment. and service and maintenance facilities.

The great size of brown coal seams (at some points thicker than 100 m) results in the creation of massive holes during mining. As the overburden thickness is generally around 10 m, there is not enough material to refill these holes (Holmes (1993)). Consequently, rehabilitation presents greater difficulties than for black coal (see, for example, Woodward-Clyde (1999)).

‡‡ Requires vast storage volume, which is costly to provide. Additionally, it is a safety hazard, as drying brown coal is prone to spontaneous combustion.

§§ Loy Yang, the largest of the mines, produces 30.5 Mt of coal annually (Loy Yang Power (1999)).

4.3.3.1.2 Material Flows

4.3.3.1.2.1 Assumptions

An average brown coal mine has the characteristics of the weighted production (mass) average of the existing three Latrobe Valley mines: Yallourn (18 Mtpa), Morwell (17.6 Mtpa), and Loy Yang (30.5 Mtpa) (Yallourn Energy (1999), Hazelwood Power (1999), Loy Yang Power (1999)).

4.3.3.1.2.2 Material Requirements

Table 4.3.21 shows the materials used in an average brown coal mine. Omissions include a number of minor materials, for example, chemicals and maintenance requirements for all equipment.

Table 4.3.21: Material requirements for the mining of 1 Mt of brown coal from an average mine.

Material	GWh	Ref.
Electricity	4.25	A1
	kg	Ref.
Brown Coal	1.00×10^9	Basis
Overburden	3.70×10^8	A2
Diesel	6.67×10^4	A3
Petrol	1140	A4
Lubricating Oil	85	A5
Water (low quality)	8.52×10^7	A6

4.3.3.1.2.3 Material Emissions

Table 4.3.23 shows the material emissions from an average brown coal mine. Dust emissions when mining coal with moisture content over 10 % the amount are less than 1 g per Mt of raw coal mined (NPI (1999a)). Thus, as brown coal has moisture contents of 60-66 % (see Figure 4.3.4), dust generation is negligible.

4.3.3.1.3 Economic Flows

Table 4.3.22 shows the capital costs, I, with capacity, Q (Equation 4.3.26), and operating costs, O & M, with production, P (Equation 4.3.27) for brown coal mining.

Table 4.3.23: Material emissions from the mining of 1 Mt of brown coal from an average mine.

Material	kg	Ref.
Brown Coal	1.00×10^9	Basis
Overburden	3.70×10^8	A7
Oily Waste	881	A8
Water (low quality)	3.12×10^8	A9
Carbon dioxide	2.12×10^5	A10
Methane	30.9	A11
NMVOC	325	A12
N_2O	6.04	A13
NO_x	3020	A14
CO	1170	A15
SO_2	612	A16

Table 4.3.22: Correlation parameters for the capital and operating costs of brown coal mining.

Equation	A	ψ	Range		Data Ref
			I ($ million (AUD 2000))	Q (Mtpa)	
Equation 4.3.26	194	0.536	134 - 1746	0.5 - 60	A1
Equation	B	ω	O & M ($ million (AUD 2000) per annum)	P (Mtpa)	Data Ref
Equation 4.3.27	13.7	0.593	9.10 - 155	0.5 - 60	A2

4.3.3.1.4 Social Flows

Table 4.3.24 shows the social flows in average brown coal mining. Reports of LTI and fatalities are for the mining, transport, and generation subsystems together (see Section 4.3.3.3.4). One estimate of mining LTIF is 9.4 LTI per 10^6 WH and indicates no fatalities for at least 8 years (Natural Resources and Environment (2001)).

Table 4.3.24: Employment, LTI and fatalities data for an average brown coal mine.

Parameter	Value per Mtpa	Ref.
Employment	11.8	A1

4.3.3.2 TRANSPORT SUBSYSTEM

4.3.3.2.1 Description of the Transport Subsystem

Transport of brown coal involves the use of conveyors. Between the mine and power station is the raw coal bunker (see Section 4.3.3.1). Transport of equipment and personnel uses rubber tyred vehicles. Other infrastructure includes motors, conveyor transport equipment, switching stations, dust minimisation equipment, and service and maintenance facilities.

4.3.3.2.2 Material Flows

4.3.3.2.2.1 assumptions

A brown coal conveyor has energy consumption equivalent to a black coal conveyor. The distance traversed by the conveyor is 4 km. Mass lost between the mine and the power station is 0.0005 % of the mass transferred, of which 1 % is dust and the remainder is solid waste.

4.3.3.2.2.2 Material Requirements

Table 4.3.25 shows the materials used in average brown coal transport. This analysis omits a number of material requirements, for example, water, chemicals and maintenance materials.

Table 4.3.25: Material requirements for the transport of 1 Mt of brown coal from an average mine to power station.

Material	GWh	Ref.
Electricity	0.643	A1
	kg	Ref.
Brown Coal	1.00×10^9	Basis

4.3.3.2.2.3 Material Emissions

Table 4.3.26 shows the material emissions from average brown coal transport.

Table 4.3.26: Material emissions from the transport of 1 Mt of brown coal from an average mine to power station.

Material	kg	Ref.
Brown Coal	1.00 x 108	A2
Solid waste	4950	A3
Particulates	50	A4

4.3.3.2.3 Economic Flows

Table 4.3.27 shows the capital costs, I, with capacity, L.Q (Equation 4.3.28), and operating costs, O & M, with production, L.P (Equation 4.3.29) for brown coal transport.

Table 4.3.27: Correlation parameters for the capital and operating costs of brown coal transport.

Equation	A	ψ	Range: I ($ million (AUD 2000))	Range: L.Q (km.Mtpa)	Data Ref
Equation 4.3.28	19.1	0.5	58 - 1721	1.75 - 3660	A1
Equation	**B**	**ω**	**O & M ($ million (AUD 2000) per annum)**	**L.P (km.Mtpa)**	**Data Ref**
Equation 4.3.29	1.93	0.421	2.44 - 60.9	1.75 - 3660	A2

4.3.3.2.4 Social Flows

Reports of employment, LTI and fatalities for transport are contained in the combined mining, transport, and generation subsystem estimate (see Section 4.3.3.3.4).

4.3.3.3 GENERATION SUBSYSTEM

4.3.3.3.1 Description of the Generation Subsystem

As with black coal, electricity generation from brown coal uses steam turbine systems (see Figure 4.3.2). However, brown coal is a very different fuel to black coal (see Figure 4.3.4), which necessitates considerable modification of the standard designs used for black coal steam turbine systems. Firstly, the softer brown coal fuel requires only low-impact fan milling for size reduction. Secondly, the high moisture level (up to 2 tonnes of water per tonne of dry coal) increases the volume of flue gas generated on combustion. Thus, to accommodate this extra moisture the size of the boiler is increased. Thirdly, the vaporisation of this higher moisture consumes a greater proportion of the heat generated from fuel combustion, reducing the amount available to generate steam. Consequently, rather than efficiencies of up to the high 30's, efficiencies can only reach the low 30's, resulting in greater emissions of most gases for the same output of electricity. Contrariwise, brown coal systems emit less NO_x than do black coal systems. Considerable NO_x forms in the boiler due to oxidation of N_2 at high temperatures. The high moisture level of brown coal ensures that the combustion temperature is lower for brown coal than black coal. Lastly, electrostatic precipitation is the preferred method of extracting small ash particles, from the flue gases.

Other differences include the use of water to transport ash to dumping sites, and the use of cooling towers for three plants, and once-through lake cooling for the other plant.

Substantially improving the efficiency of brown coal generation requires the reduction of coal water content before combustion. A promising technology for water removal is Mechanical Thermal Expression (or MTE). The MTE technique utilises heat and pressure in combination to force the moisture from the coal as liquid. This can reduce water contents from 60-66 % to 20-30 % moisture content (or 0.75-1.4 kg water removed per kg dried coal), and double the energy density (energy content per mass) of the brown coal fuel (Strauss *et al.* (2001)***). This increases electricity generation efficiency, as less heat is required for water vaporisation. In combination with the IGCC technology, discussed in Section 4.3.2.2.2 (see Figure 4.3.3), some have predicted electrical efficiencies as high as 48 % (McIntosh (2003)). Reducing the moisture in the fuel also results in less water vapour production. Thus, the flue gas has a reduced volume, and the boiler and flue gas parts can be of smaller size. As boiler cost is one of the largest contributors to capital costs, this size reduction can substantially decrease the capital costs of a power station.

*** Additionally many publications of the CRC for Clean Power from Lignite describe the effects of MTE dewatering on efficiencies with ST and IGCC electricity generation technologies (i.e. Kealy *et al.* (2001)).

4.3.3.3.2 Material Flows

4.3.3.3.2.1 Assumptions

The steam turbine technology data estimates are averages of all Victorian brown coal power stations. The basis for the IGCC technology data estimates is a report produced by the proponent (Department of Energy (U.S.A.) (2000)). Section 4.3.2.3.2.1 explains the bases for the choice of this technology for black coal. The brown coal IGCC uses the same technology to ensure comparability between the two fuels. The brown coal IGCC technology also employs the MTE technology (see Section 4.2.3.3). The reported performance and emissions for the IGCC are based on a ProSim© process simulation. The basis for data in this section is GWh of electricity generated, rather than GWh of electricity sent out.

4.3.3.3.2.2 Material Requirements

Table 4.3.28 shows the materials used in an average brown coal power station. Lubricating oils consumption estimated from emissions of oily waste.

4.3.3.3.2.3 Material Emissions

Table 4.3.29 shows the materials emitted from an average brown coal power station. Assumed ash density is 900 kg per m^3. Simple mass balances validate the carbon dioxide and SO_2 emissions results.

4.3.3.3.3 Economic Flows

Table 4.3.30 shows the capital costs, I, of steam turbine (Equation 4.3.32) and IGCC technologies (Equation 4.3.33), with production capacity, Q. The basis of the brown coal IGCC capital and operating cost estimations are reported costs for black coal IGCC systems, modified by replacing the coal preparation costs of such systems with a predicted cost for the MTE coal drying technology (MTE cost estimate from McIntosh (2003)). These costs assume that the technology is mature. The first IGCC system is likely to have considerably greater costs. As the MTE and IGCC technologies for brown coal have yet to be tested, these cost estimates have high uncertainties.

Table 4.3.28: Material requirements for the generation of 1 GWh of electricity in an average brown coal power station.

Material	ST		IGCC	
	GWh	Ref.	GWh	Ref.
Electricity	0.0801	A1	0.0545	B1
	kg	Ref.	kg	Ref.
Coal	1.39×10^6	A2	7.19×10^5	B2
Fuel Oil	177	A3		
Briquettes	871	A4		
Natural Gas	13.9	A5	7320	B3
Diesel	0.441	A6	0.446	B4
Petrol	5.59	A7	5.65	B5
LPG	5.01	A8		
Sulfuric Acid	382	A9	334	B6
Caustic Soda	38.1	A10	947	B7
Brine solution (SG 1.2)	63.5	A11		
Aluminium Sulfate (SG1.3)	15.9	A12	1.86	B8
Eliminox	0.68	A13		
Ammonia	0.113	A14	9.3	B9
Trisodium Phosphate	0.793	A15		
Polymer	13.4	A16		
Anti Scalant treatment	0.732	A17	0.62	B10
Chlorine			7.44	B11
Hydrazine			0.248	B12
Bromide			0.93	B13
Hydrochloric Acid			0.248	B14
Antifoam			0.248	B15
Lubricating Oil	3.85	A18	1.7	B16
Water (low quality)	2.48×10^6	A19	1.40×10^5	B17
Water (high quality)	9.25×10^4	A20	4.24×10^5	B18

Equation 4.3.30 and Equation 4.3.31 show the operating costs, O & M, for brown coal steam turbine and IGCC power plants, with annual production, P (GWhpa), and capacity, Q (MW) (Data Refs. A2 and B2).

$$O \& M = \$\, 4.51\, (P) + \$\, 31.5\, (Q)$$

Equation 4.3.30

for: any P and Q.

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Table 4.3.29: Material emissions from the generation of 1 GWh of electricity in an average brown coal power station.

Material	ST		IGCC	
	GWh	Ref.	GWh	Ref.
Electricity	1.08	A21	1.05	B19
	kg	Ref.	kg	Ref.
Ash	2.07×10^4	A22	6520	B20
Solid Waste			6520	B21
Lubricating Oil	4.39	A23	1.70	B22
Evaporation	1.37×10^6	A24	4.15×10^5	B23
Wastewater	9.26×10^5	A25	4.70×10^5	B24
Sewerage	0.0273	A26	0.0265	B25
Saline water	1.30×10^5	A27	2.54×10^4	B26
Carbon dioxide	1.15×10^6	A28	7.03×10^5	B27
Methane	6.09	A29	301	B28
NMVOC	20.6	A30	2.54	B29
N_2O	16.8	A31	9.75	B30
NOx	1590	A32	165	B31
CO	210	A33	196	B32
SO2	1810	A34	1840	B33
Particulates	469	A35	20	B34

Table 4.3.30: Correlation parameters for the capital costs of brown coal generation.

Equation	A	ψ	Range		Data Ref.
			I ($ million (AUD 2000))	Q (MW)	
Equation 4.3.32	9.37	0.786	1900 - 6320	1000 - 4000	A1
Equation 4.3.33	10.5	0.663	517 - 941	357 - 883	B1

$$O \& M = 0.743(P)^{0.479}$$

Equation 4.3.31

for: P = 1373 to 3203 GWh per annum and O & M = $ 19.7 to 29.6 million per annum.

4.3.3.3.4 Social Flows

Table 4.3.31 shows the social flows in average brown coal generation. LTIF for steam turbines is 5.6 LTI per 10^6 WH. Actual WH per employee information for brown coal generation is not available. The value used, 1987 WH per employee, is for brown coal mining (Natural Resources and Environment (2001)). This estimate combines LTI and fatalities for mining, transport, and generation subsystems, and employment for transport and generation. No fatalities in this subsystem was reported.

Table 4.3.31: Employment, LTI and fatalities data for average brown coal electricity generation.

Parameter	Steam Turbine		IGCC	
	Value per GWhpa	Ref.	Value per km	Ref.
Employment	0.018	A1	0.018	B1
LTI	0.0038	A2	0.0038	B2
Fatalities	0		0	

4.3.3.4 Transmission Subsystem

4.3.3.4.1 Description of the Transmission Subsystem

Section 4.3.2.3.2 discusses electricity transmission. Like black coal, brown coal electricity generation systems are situated near brown coal mines, and distant from major electricity consumers.

4.3.3.4.2 Material Flows

Table 4.3.32 shows the material consumption and emissions for average transmission. The average transmission distance traversed by electricity generated from brown coal in Australia is 279 km. It is greater than for black coal due to greater exports of electricity from Victoria. See Section 4.3.2.4.2.1 for assumptions.

Table 4.3.32: Material requirements and emissions for the transmission of 1 GWh of electricity from an average brown coal power station.

In	GWh	Ref.	Out	GWh	Ref.
Electricity	1	Basis	Electricity	0.979	A1

4.3.3.4.3 Economic Flows and Social Flows

See Section 4.3.2.4.3 for capital and operating cost data. See Section 4.3.2.4.4 for employment, LTI and fatalities data.

4.3.4 Natural Gas and LNG

4.3.4.1 Mining Subsystem

4.3.4.1.1 Description of the Mining Subsystem

The mining subsystem[†††] of the natural gas system is much different to that of the coal systems, because natural gas exists in nature as a gas, rather than a solid. Thus, instead of using the crushing and carrying equipment (used in coal processing), the natural gas mining process must use drilling and pumping equipment. Natural gas also exists with other hydrocarbons, such as liquefied petroleum gas (LPG) sources, condensates and crude oils, which have other uses, and water, and gases like hydrogen sulphide (H_2S), carbon dioxide (CO_2) and nitrogen (N_2), which must be removed before it can safely be used. The amounts and types of contaminants will vary with well location.

The first requirement is to find the natural gas. Natural gas commonly collects in particular sedimentary rock formations, such as anticlines (upward folds in rock layers) and faults (fractures where layers are broken) (EPA (U.S.A.) (1999)). It can occur both on land and offshore. Searching for natural gas requires the use of geological methods, such as aerial photographs and MAD (Magnetic Anomaly Detection), rock outcrop studies, gravity surveys, remote sensing, core samples, seismic surveys, high-energy common depth point (CDP) and 'wildcat' (test) drilling (EPA (U.S.A.) (1999), Speight (1993)), and exploratory drilling. Rotary drilling is the standard method, because it is rapid, efficient, economical, and can reach depths of 9150 m (Speight (1993)). The drill bit is rotated to chip off pieces of rock, thus increasing the hole depth (EPA (U.S.A.) (1999)). A drilling fluid enters through many hollow pipes, and returns to the surface through the annular space between the hollow pipes and the rock wall (Speight (1993)). Once the well reaches the required depth, it is lined with cemented material called casing (Katz and Lee (1990)). Perforation of the casing allows the gas to enter the well and completes the well (Katz and Lee (1990)). A production system is then developed, usually consisting of a producing well, wellhead, manifold, phase separation equipment, loading facility or transport terminal, and support systems (MMS (1998)).

The second requirement is to extract the hydrocarbons. Gas usually exits spontaneously, as long as there is adequate pressure within the reservoir. Then it passes

[†††] Mining refers to what are commonly known as exploration, development, production, and processing.

through phase separation equipment, which also removes any solid impurities, and separates the liquid and gas for transport. Gas transportation is by pipeline to a processing plant, which is usually on land. Gas processing extracts hydrocarbons such as propane and butane for sale, and removes unwanted components such as water, carbon dioxide (CO_2), hydrogen sulphide (H_2S), mercury, and aromatics (or BETX's). The product after cleaning is natural gas.

4.3.4.1.2 Material Flows

4.3.4.1.2.1 Assumptions

Data in this section refers to natural gas production and processing facilities in all Australian states. The basis for much of the included data is APPEA (1999), which includes 98 % of Australia's oil and gas industry. The material consumption and emissions data includes contributions from Australian exploration and development activities (see Section 4.3.4.1.1). It includes both failed and successful exploration. In 1997 there were 376 producing wells, and a production rate of 50423 kt of hydrocarbon (26.1 % natural gas), and thus each producing well produces 134 kt of hydrocarbon, with 35.1 kt of natural gas (AGSO (1998), APPEA (1999)).

4.3.4.1.2.2 Material Requirements

Table 4.3.34 shows the materials used in average natural gas mining. Natural gas consumption includes natural gas for delivery, natural gas consumed internally for heat and electricity, and natural gas flared or leaked. Omission of chemicals is due to difficulties identifying individual chemical use. Information sources state only the combined use, 600 tpa (UKOOA (1999))[‡‡‡]. Explosives use in seismic surveys is not reported.

4.3.4.1.2.3 Material Emissions

Table 4.3.33 shows the material emissions from average natural gas mining.

[‡‡‡] EPS (Canada) (1989) estimate that oil and gas operators use over 700 different chemicals.

Table 4.3.34: Material requirements for the production of 1 kg of mixed petroleum products from an average natural gas mining subsystem.

Material	kg	Ref.
Natural Gas	0.476	A1
Diesel	4.58×10^{-3}	A2
Petrol	1.31×10^{-6}	A3
Aviation Fuel	3.71×10^{-4}	A4
Crude Oil	1.66×10^{-4}	A5
Drilling Solids	1.15×10^{-3}	A6
Water (low quality)	0.0392	A7

Table 4.3.33: Material emissions from the production of 1 kg of mixed petroleum products in an average natural gas mining subsystem.

Material	kg	Ref.
Natural Gas	0.396	A8
Crude Oil	1.65×10^{-4}	A9
Drilling Fluid Waste	4.28×10^{-3}	A10
Drill Cuttings	2.34×10^{-3}	A11
Produced Sand	1.34×10^{-4}	A12
Solid Waste	1.30×10^{-4}	A13
Water (low quality)	0.0361	A14
Sewerage	5.01×10^{-6}	A15
Produced Water	0.647	A16
Carbon dioxide	0.336	A17
Methane	3.56×10^{-3}	A18
NMVOC	1.35×10^{-3}	A19
N_2O	1.86×10^{-5}	A20
NO_x	2.12×10^{-3}	A21
CO	5.94×10^{-4}	A22
SO_2	1.95×10^{-4}	A23
Particulates	1.02×10^{-4}	A24
H_2S	4.19×10^{-11}	A25

4.3.4.1.3 Economic Flows

Table 4.3.35 shows the capital costs, I, of production (Equation 4.3.34) and processing (Equation 4.3.35), with production capacity, Q.

Table 4.3.36 shows the operating costs, O & M, of production (Equation 4.3.36) and processing (Equation 4.3.37), with yearly production, P. The costs of LNG processing are included in the transport subsystem (see Section 4.3.4.2.3). Published cost estimates for operating natural gas mining facilities are rare, and thus these operating cost estimates have high uncertainties.

Table 4.3.35: Correlation parameters for the capital costs of natural gas mining.

Equation	A	ψ	Range: I ($ million (AUD 2000))	Range: Q (Mtpa)	Data Ref
Equation 4.3.34	418	0.757	91.3 - 3200	0.134 - 14.7	A1
Equation 4.3.35	96.3	0.881	7.96 - 2010	0.1 - 31.5	B1

Table 4.3.36: Correlation parameters for the operating costs of natural gas mining.

Equation	B	ω	Range: O & M ($ million (AUD 2000) per annum)	Range: P (Mtpa)	Data Ref
Equation 4.3.36	13.7	1.22	102 - 9280	5.17 - 209	A2
Equation 4.3.37	86.4	1.00	292 - 486	3.38 - 5.62	B2

4.3.4.1.4 Social Flows

Table 4.3.37 shows the social flows in average natural gas and LNG mining. LTIF for oil and gas production is 5.5 and 11.6 LTI per 10^6 WH for employees and contractors respectively for 1931 WH per employee. Employees allocated between oil, LNG and natural gas using mass production.

4.3.4.2 TRANSPORT SUBSYSTEM

4.3.4.2.1 Description of the Transport Subsystem

Natural gas transport within Australia is exclusively by pipeline. On long pipelines, intermediate, unmanned compressor stations are required to maintain pressure within the pipeline. While natural gas storage is possible, this assessment assumes no storage,

Table 4.3.37: Employment, LTI and fatalities data for average natural gas and LNG mining.

Parameter	Natural Gas: Value per Mtpa	Natural Gas: Ref.	LNG: Value per Mtpa	LNG: Ref.
Employment	187	A1	166	B1
LTI	4.61	A2	4.61	B2
Fatalities	0.011	A3	0.011	B3

as in use currently are only two small storage facilities: Iona, Victoria (underground) and Dandenong, Victoria (LNG).

Liquefaction enables natural gas transport over long distances, where pipeline transport is infeasible. Natural gas does not liquefy until about -161 °C, and thus requires substantial cooling. This cooling process is highly energy intensive. There is currently only one Australian LNG plant (Karratha, WA). LNG can be stored in large quantities before transport. LNG transport from Australia is by sea. LNG transport vessels consume a part of their cargo to power the vessel, and consume fuel oil when empty and on return journeys. Japan and South Korea consume most Australian LNG, but the U.S.A. has consumed some in the past. On delivery, LNG can be stored in large quantities, and vaporised when needed. Vaporisation is by heat exchange with seawater. When the water temperature is too low, the consumption of some of the vaporised LNG may also be necessary (Carlson (1996)). Final transport to power stations is by transmission pipeline.

4.3.4.2.2 Material Flows

4.3.4.2.2.1 Assumptions

The basis for much of the domestic gas transport, material emissions flows data is AGA (1997), which includes 89 % of Australia's gas transmission by flow volume. The material flows assume natural gas delivery to power stations is through high-pressure transmission lines. The average length of these domestic pipelines is 927 km (from AGSO (1998), NGGIC (1998a)[§§§]). LNG transport is to Japan only, 6800 km. LNG assumes a short (15 km) pipeline delivers vaporised gas to power stations.

4.3.4.2.2.2 Material Requirements

Table 4.3.38 shows the materials used in average natural gas and LNG transport. Water use in pipeline transport is minimal. Natural gas consumption for LNG production is included in the mining subsection. The estimate assumes no supplemental LPG use in LNG transport (LPG may be used to boost the vaporised LNG's energy content where necessary).

§§§ Weighted average based on mass flow through all major pipelines.

Table 4.3.38: Material requirements for the transport of 1 kg of natural gas or LNG from an average natural gas mining subsystem to power station.

Material	Pipeline		LNG	
	GWh	Ref.	GWh	Ref.
Electricity	6.19×10^{-10}	A1	1.13×10^{-8}	B1
	kg	Ref.	kg	Ref.
Natural Gas	1	Basis	1	Basis
Fuel Oil			0.0348	B2
Diesel	3.94×10^{-5}	A2	6.23×10^{-7}	B3
Petrol	1.22×10^{-5}	A3	3.85×10^{-7}	B4
LPG	1.40×10^{-7}	A4	4.43×10^{-9}	B5
Water (low quality)			17.7	B6

4.3.4.2.2.3 Material Emissions

Table 4.3.39 shows the material emissions from average natural gas and LNG transport.

Table 4.3.39: Material emissions from the transport of 1 kg of natural gas or LNG from an average natural gas mining subsystem to power station.

Material	Pipeline		LNG	
	GWh	Ref.	GWh	Ref.
Natural Gas	0.989	A17	0.977	B10
Solid Waste			4.02×10^{-5}	B11
Wastewater			17.7	B12
Carbon dioxide	0.0304	A18	0.129	B13
Methane	3.86×10^{-4}	A19	4.87×10^{-4}	B14
NMVOC	7.84×10^{-5}	A20	9.85×10^{-5}	B15
N_2O	5.55×10^{-8}	A21	4.82×10^{-6}	B16
NO_x	1.89×10^{-6}	A22	3.46×10^{-4}	B17
CO	2.03×10^{-5}	A23	2.59×10^{-5}	B18
SO_2	3.70×10^{-7}	A24	2.07×10^{-4}	B19
Particulates	9.35×10^{-6}	A25	2.82×10^{-5}	B20
H_2S	4.17×10^{-10}	A26	5.20×10^{-10}	B21

4.3.4.2.3 Economic Flows

Equation 4.3.38 and Equation 4.3.39 show the capital cost, I, of natural gas and LNG transport, with annual production capacity, L.Q respectively (Data Ref. A1 and B1).

$$I = 2.15(L.Q)^{0.735}$$

Equation 4.3.38

for: L.Q = 492 to 50435 km.Mtpa and I = \$ 204 to 6120 million (AUD 2000).

$$\begin{aligned} I = {} & 0.622(Q)^{0.854} && \text{(LNG production)} \\ & +[114+0.0049(L_O)](Q) && \text{(Ocean transport)} \\ & +151(Q) && \text{(Vaporisation)} \\ & +2.15(L_P.Q)^{0.735} && \text{(Pipeline)} \end{aligned}$$

Equation 4.3.39

for: Q = 4.8 to 8.3 Mtpa, L_o = 6800 km, L_p = 15 km and I = \$ 6.16 to 10.6 billion (AUD 2000).

The operating costs, O & M (in \$ million (2000) per annum), of natural gas and LNG transport, with annual transport task, L.Q (km.Mtpa), are shown in Equation 4.3.40 (Data Ref. A2) and Equation 4.3.41 (Data Ref. B2).

$$O\&M = 1.61(L.P)^{0.620}$$

Equation 4.3.40

for: L.P = 34.5 to 208000 km.Mtpa and O & M = \$ 14.4 to 3170 million (AUD 2000) per annum.

$$O\&M = 15.9(L_O.P)^{0.442} + 1.61(L_P.P)^{0.620}$$

Equation 4.3.41

for: P=2 to 22 Mtpa, L_0 = 6800 km (ocean), L_p (pipeline) = 15 km and O & M = \$ 763 to 6990 million (AUD 2000) per annum.

4.3.4.2.4 Social Flows

Table 4.3.40 shows the social flows in average natural gas and LNG transport. LTIF for pipeline transport is 3.2 LTI per 10^6 WH for 1931 WH per employee. LTIF for LNG ship transport is 0.48 LTI per 10^6 WH for 1949 WH per employee. Employment excludes employees in natural gas regasification facilities.

Table 4.3.40: Employment, LTI and fatalities data for average natural gas and LNG transport.

Parameter	Steam Turbine		IGCC	
	Value per Mtpa	Ref.	Value per Mtpa	Ref.
Employment	0.0477 ****	A1	23.7	B1
LTI	0.186	A2	0.315	B2
Fatalities	0.00706	A3	0.00305	B3

4.3.4.3 GENERATION SUBSYSTEM

4.3.4.3.1 Description of the Generation Subsystem

Unlike black and brown coals, no one electricity generation technology dominates for natural gas. A survey, by the author, of currently used technologies in 2000, showed equal installed capacities of steam turbine and open cycle gas turbine technologies in Australia, and little combined cycle gas turbine technology capacity. Additions since 2000 include a large combined cycle gas turbine plant (486 MW), and a number of open cycle gas turbine projects.

Steam turbine technology is similar for natural gas and black coal (see Figure 4.3.2). However, natural gas plants do not store fuel, require no mills, and as they produce no ash, ash removal is not necessary. Efficiencies for these plants are similar to black coal plants (mid to low 30's). This technology was once standard for natural gas, until the development of high efficiency gas turbines in the 1960's reduced their use.

Gas turbine systems produce electricity without the need for steam generation (Figure 4.3.6). They use the heat and momentum of flue gases from fuel combustion to turn the turbine blades. A rotating compressor provides air for combustion at elevated pressure to the combustor. The compressor typically requires 50 % of the power generated (Smith (1996)). Mixing of the air and fuel occurs in a separate combustion chamber, before the turbine. The flue gas immediately enters the turbine. Release of the flue gases to atmosphere occurs after the turbine. Only minimal cooling is required, and thus water consumption is much lower than for steam turbine systems. Their simple design enables them to start generating electricity quicker than other technologies. Consequently, it is the preferred technology for when the demand for

**** employees per km.

electricity rapidly increases. These systems have a wide range of efficiencies, 17-37 % in Australia, due to rapid advances in their design.

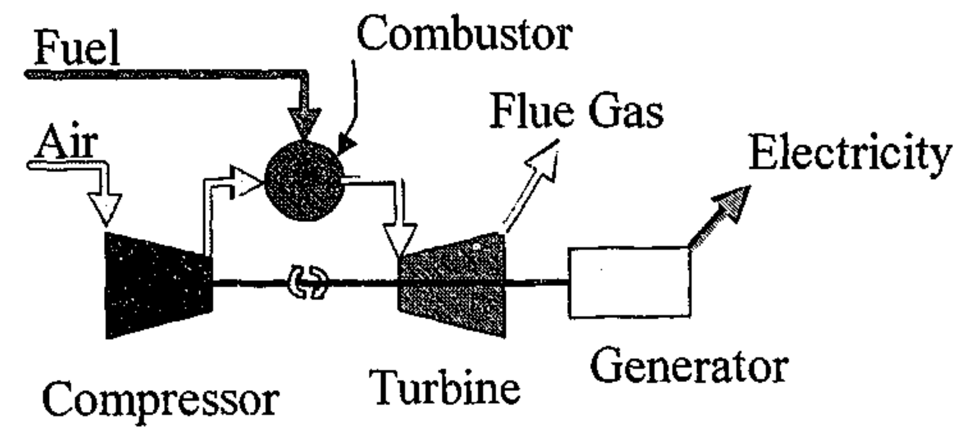

Figure 4.3.6: Simplified representation of the open cycle gas turbine electricity generation technology.

The combined-cycle gas turbine technology is the combination of an open cycle gas turbine with a steam turbine (Figure 4.3.7). The flue gas from the gas turbine provides the heat source to generate steam in a heat recovery steam generator (HRSG). This technology can generate electricity at efficiencies approaching 60 %.

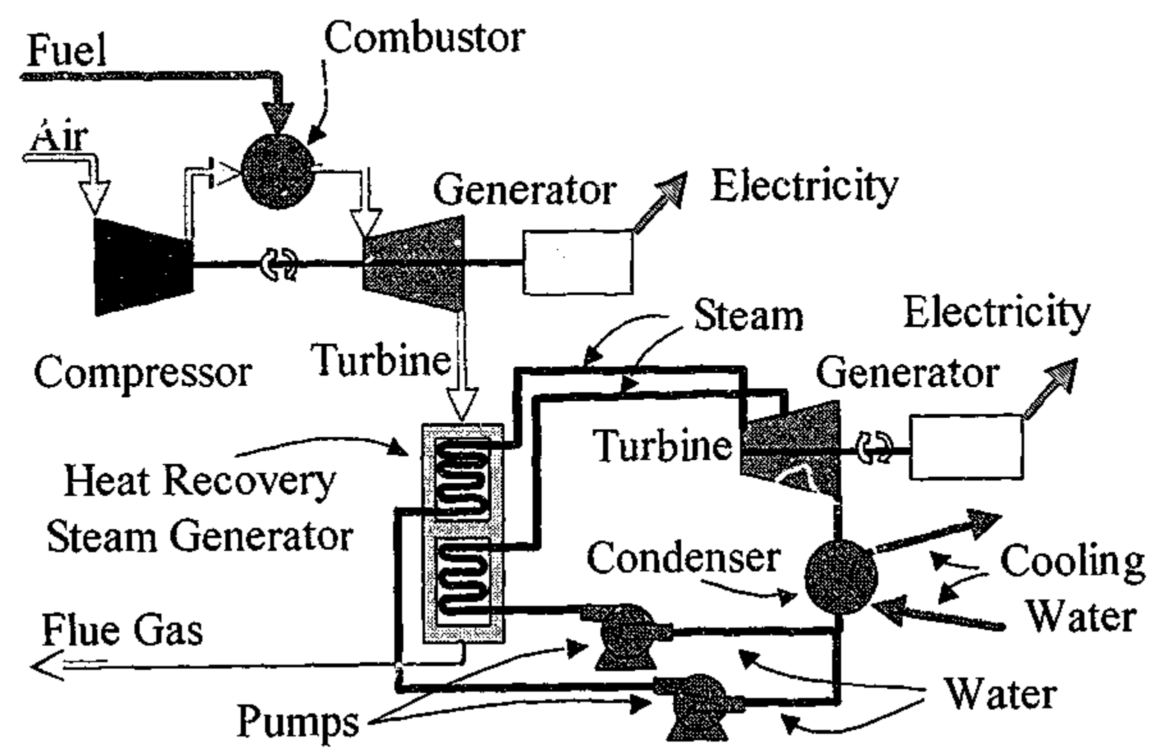

Figure 4.3.7: Simplified representation of the combined cycle gas turbine electricity generation technology.

Consumption of LNG occurs after vaporisation, and thus the same technologies (and range of efficiencies) apply as for natural gas.

4.3.4.3.2 Material Flows

4.3.4.3.2.1 Material Requirements

Table 4.3.41 shows the materials used in average natural gas power stations. Minor mass rate air emissions, such as heavy metals (from auxiliary fuel) and large hydrocarbons are omitted from the analysis.

4.3.4.3.2.2 Material Emissions

Table 4.3.42 shows the material emissions from average natural gas power stations.

4.3.4.3.3 Economic Flows

Table 4.3.43 shows the capital costs, I, of steam turbine (Equation 4.3.42), OCGT

Table 4.3.41: Material requirements for the production of 1 GWh of electricity from an average natural gas power station.

Material	ST		OCGT		CCGT	
	GWh	Ref.	GWh	Ref.	GWh	Ref.
Electricity	0.0471	A1	0.0293	B1	0.0531	C1
	kg	Ref.	kg	Ref.	kg	Ref.
Natural Gas	2.01×10^5	A2	2.74×10^5	B2	1.40×10^5	C2
Fuel Oil			321	B3	164	C3
Diesel	0.462	A3	0.301	B4	0.112	C4
Petrol	5.85	A4	3.82	B5	1.42	C5
LPG	5.25	A5	3.42	B6	1.28	C6
Sulfuric Acid	49.8	A6	0.122	B7	28.9	C7
Caustic Soda	19	A7	0.0498	B8	11.3	C8
Ammonia	0.606	A8			0.228	C9
Chlorine	6	A9			2.26	C10
Hydrazine	0.2	A10			0.0752	C11
Ferrous Sulphate	8.68	A11			3.27	C12
Trisodium Phosphate	0.793	A12			0.298	C13
Lubricating Oil	0.688	A13	0.165	B9	0.362	C14
Water (low quality)	1.32×10^8	A14			2.37×10^7	C15
Water (high quality)	6.47×10^4	A15	256	B10	1.14×10^5	C16

Table 4.3.42: Material emissions from the production of 1 GWh of electricity in an average natural gas power station.

Material	ST		OCGT		CCGT	
	GWh	Ref.	GWh	Ref.	GWh	Ref.
Electricity	1	A19	1	B11	1	C17
	kg	Ref.	kg	Ref.	kg	Ref.
Ash	0.214	A20			0.0164	C18
Oily Wastes	0.688	A21	0.165	B12	0.362	C19
Evaporation	9.66×10^5	A22			4.87×10^5	C20
Wastewater	1.32×10^8	A23	95.1	B13	2.33×10^7	C21
Sewerage	0.0266	A24	0.0186	B14	6.95×10^{-3}	C22
Carbon dioxide	6.15×10^5	A25	7.20×10^5	B15	3.80×10^5	C23
Methane	1.28	A26	95.4	B16	15.9	C24
NMVOC	7.83	A27	22.1	B17	8.9	C25
N_2O	1.2	A28	1.41	B18	6.97	C26
NO_x	1400	A29	2300	B19	497	C27
CO	194	A30	533	B20	23.9	C28
SO_2	0.038	A31	2.98	B21	3.47	C29
Particulates	15.6	A32	252	B22	22.9	C30

Table 4.3.43: Correlation parameters for the capital costs of natural gas generation.

Equation	A	ψ	Range: I ($ million (AUD 2000))	Range: Q (MW)	Data Ref
Equation 4.3.42	4.06	0.803	177 - 1039	110 - 1000	A1
Equation 4.3.43	1.13	0.881	4.7 - 271	5 - 500	B1
Equation 4.3.44	11.3	0.593	140 - 451	70 - 500	C1

(Equation 4.3.44) and CCGT (Equation 4.3.43) technologies, respectively, with production capacity, Q.

Table 4.3.44 shows the operating costs, O & M, of steam turbine (Equation 4.3.45), OCGT (Equation 4.3.46) and CCGT (Equation 4.3.47) technologies, respectively, with

Table 4.3.44: Correlation parameters for the operating costs of natural gas generation.

Equation	B	ω	Range: O & M ($ million (AUD 2000) per annum)	Range: P (GWhpa)	Data Ref
Equation 4.3.45	0.00606	0.917	2.54 - 19.2	723 - 6570	A2
Equation 4.3.46	0.387	0.676	0.31 - 14.7	22 - 6570	B2
Equation 4.3.47	0.00234	0.826	2.64 - 27.4	307 - 5220	C2

yearly production, P.

4.3.4.3.4 Social Flows

Table 4.3.45 shows the social flows in average natural gas generation. No LTI figures are available for natural gas plants. Values assume negligible LTIF of 0.1 LTI per 10^6 WH and 1373 WH per employee. In addition to the employment listed for steam turbine and OCGT power stations, they require 13 and 6 administration employees respectively.

Table 4.3.45: Employment, LTI and fatalities data for average natural gas electricity generation.

Parameter	Steam Turbine		OCGT		CCGT	
	per MW	Ref.	per MW	Ref.	per GWhpa	Ref.
Employment	0.044	A1	0.021	B1	0.0095	C1
Parameter	per GWhpa	Ref.	per GWhpa	Ref.	per GWhpa	Ref.
LTI	1×10^{-6}	A2	1×10^{-6}	B2	1×10^{-6}	C2
Fatalities	0		0		0	

4.3.4.4 Transmission Subsystem

4.3.4.4.1 Description of the Electricity Transmission Subsystem

Section 4.3.2.3.2 discusses electricity transmission. Unlike black coal and brown coal, delivery of natural gas to major electricity consumption centres is common. Thus, natural gas electricity generation systems are often near major electricity consumers, and transmission distances are much shorter than in black and brown coal systems.

4.3.4.4.2 Material Flows

Table 4.3.46 shows the material consumption and emissions for average transmission. The average transmission distance traversed by electricity generated from natural gas in Australia is negligible, perhaps 15 km. See Section 4.3.2.4.2.1 for assumptions.

4.3.4.4.3 Economic Flows and Social Flows

See Section 4.3.2.4.3 for capital and operating cost data. See Section 4.3.2.4.4 for

employment, LTI and fatalities data.

Table 4.3.46: Material requirements and emissions for the transmission of 1 GWh of electricity from an average natural gas power station.

In	GWh	Ref.	Out	GWh	Ref.
Electricity	1	Basis	Electricity	0.999	A1

4.3.5 Data Omissions

The material flows data omits air for fuel use in fuels combustion (effectively neutral in sustainability) and emissions to air and water of heavy metals and other minor substances. Data limitations force the omission of heavy metals in all systems. The relative toxicities (CF factors) of heavy metals are high in comparison to other emissions (see Guinée *et al.* (2001)). Such materials are common in wastewaters, and are present in black and brown coals and coal ash. Thus, it is probable that implications drawn from the results of the eco- and human toxicity environmental indicators, that exclude contributions from such substances, will be uncertain. Chapter 6 examines these and other difficulties of data collection in greater depth.

The social flows data for employment is probably an underestimation, as it omits some contractor employees. In black coal systems, some of the mines included in the analysis are government owned. Often government owned mines will use in-house labour rather than contractors, and consequently the relative proportion of contract labour may be less in these systems.

Systems

4.3.6 Conversions Necessary to Produce Indicators

4.3.6.1 Overview of Conversions Necessary to Produce Indicators

The sustainability indicator methods require material, economic and social flow information. The data presented in Sections 4.3.2 to 4.3.4 is not in the form necessary to produce indicators for the systems. The basis of the present data is the output of its own subsystem (i.e. 1 Mt of black coal sent out is the basis of the black coal mining subsystem data), not the system (i.e. 1 GWh of electricity delivered). This section develops factors for conversion of the data collected from their subsystem basis to the system basis.

Sections 4.3.6.3, 4.3.6.2 and 4.3.6.4 explain the development of conversion factors for the environmental, economic and social flows.

4.3.6.2 ENVIRONMENTAL FACTORS

4.3.6.2.1 Factors to Produce System Material Flows

The conversion of material flows from subsystem basis to system basis requires three steps. The first step is to allocate material flows between products for subsystems with multiple products (see Section 3.2.3.4, Chapter 3). Two subsystems produce multiple products: black coal mining, producing domestic (BIC) and export (BICE) quality coals; and natural gas mining, producing natural gas (NG), LNG and other hydrocarbons (such as, crude oil, condensate and LPG). BIC and BICE production processes are very similar. The difference is that for BICE systems raw coal treatment includes reduction of ash content. This assessment assumes, due to a lack of data, that the ash reduction process minimally affects environmental impacts. Thus, allocation of material flows between BIC and BICE assumes they have equivalent environmental impacts per mass. Very different amounts of energy are necessary to produce each product of the natural gas mining subsystem. Combustion of gas is the primary source for this energy. An examination of Table 4.3.34 indicates that the gas is the primary material requirement. Table 4.3.33 indicates that its combustion (for energy production and flaring) and venting produce most of the emissions[††††]. Therefore, it is probable that the products requiring greatest energy will result in greatest environmental impacts. Thus, relative gas consumption is the most appropriate allocation parameter, as it reflects the physical operation of the system (see Section 3.2.3.4, Chapter 3). The allocation factors, based on relative gas consumption, are 0.758 for natural gas and 2.20 for LNG (Data Ref. A1) (see Section A2.2.1.2, Appendix 2, for derivation).

The second step is to produce factors to convert between subsystem and system bases. The product of the material flows and conversion factor of each subsystem represents the necessary material flows for that subsystem to produce 1 GWh of delivered electricity. Section A2.2.1.1 (Appendix 2) shows how to produce conversion

†††† APPEA (1999) reports that over 94 % of climate change emissions were due to energy production from gas, flaring and fugitive emissions.

factors for the ST-BIC system. Table 4.3.47 shows the conversion factors for all systems.

Table 4.3.47: Conversion factors to convert the basis of material flows data in Sections 4.3.2 to 4.3.4 from subsystem to system. Note that the natural gas mining values are the product of the conversion and allocation factors. Units: subsystem output basis per GWh of electricity delivered.

Fuel	Technology	Subsystem			
		Mining	Transport	Generation	Transmission
BIC	ST	4.56×10^{-4}	4.56×10^{-4}	1.01	1.01
	IGCC	2.56×10^{-4}	2.56×10^{-4}		
BICE	ST	6.72×10^{-4}	4.55×10^{-4}		
	IGCC	3.77×10^{-4}	2.56×10^{-4}		
BrC	ST	1.42×10^{-3}	1.42×10^{-3}	1.02	1.02
	IGCC	7.34×10^{-4}	7.34×10^{-4}		
NG	ST	1.54×10^{5}	2.03×10^{5}	1	1
	OCGT	2.10×10^{5}	2.77×10^{5}		
	CCGT	1.07×10^{5}	1.42×10^{5}		
LNG	ST	4.53×10^{5}	2.06×10^{5}		
	OCGT	6.16×10^{5}	2.80×10^{5}		
	CCGT	3.15×10^{5}	1.43×10^{5}		

The third step replaces the electricity flow with the material flows associated with its production. Just as the electricity produced will have sustainability impacts, the electricity it consumes will also have sustainability impacts. Therefore, the systems should include the material flows associated with electricity consumption. Unlike other materials, for whom exclusion of material flows is due to data availability, material flows are available for electricity. They are the sum of the converted data for each subsystem. The process involves substituting electricity consumption by a factored amount of these sums (for example, see Section A2.2.1.2, Appendix 2).

This step assumes that the source of the electricity is an identical system elsewhere. For example, the source of electricity used in a brown coal, steam turbine technology system (ST-BrC) is an identical ST-BrC. This assumption is valid for Australian black and brown coal generation, as electricity generation in the regions that they are located, is predominately produced by similar systems. The same process can replace the natural gas consumed in the BIC, BICE, and BrC generation subsystems.

This material consumption and emission data collection and manipulation corresponds to the life cycle inventory analysis (LCI) step of life cycle analysis (LCA) (see Section 3.2.4, Chapter 3).

4.3.6.2.2 Factors to Convert Material Flows to Environmental Indicators

The characterisation step of the LCA method involves the conversion of material flow data into environmental indicators, using Equation 3.2.4 (Chapter 3) (for example, see Section A2.2.1.2, Appendix 2). To use this equation, equivalency factors (CF) for each indicator and substance are necessary. CML (Guinée *et al.* (2001)) provides CF factors for most indicators, i.e. climate change, acidification, eutrophication, photochemical smog, eco-toxicity, human toxicity, resource depletion, and exergy destruction. The LCA computer program Simapro (Simapro (1999)) provides CF factors for energy. CF factors for water consumption, particulates and solid waste are unity[‡‡‡‡].

Section 3.2.3.5 (Chapter 3) acknowledges that the resource depletion CF factors are the subject of debate. For example, the choice of the appropriate reference region, R, in CF factor development (see Equation 3.2.1, Chapter 3). The CML factors use the world as reference region. However, the use of other reference regions, such as Australia, may allow a more pertinent description of the impact of resource depletion on Australia. Table 4.3.48 shows both the CML factors and factors developed for this assessment using Australia as the reference region.

4.3.6.2.3 Factors to Normalise Economic Indicators to the Australian Region

Normalisation is an optional, but recommended step for environmental indicators (see Section 3.2.3.5, Chapter 3). Normalisation involves division of system environmental indicators by regional environmental indicators (for example, see Section A2.3, Appendix 2). These regional indicators are readily available for some regions, such as Western Europe, and for the world (see Guinée *et al.* (2001)). Australia normalisation factors are less widely available. Previous LCA studies have produced normalisation factors for energy consumption, water consumption, climate change, acidification,

[‡‡‡‡] Assumes the consumption of high and low quality water has equivalent effects on total water consumption, and that the environmental impacts of particulate and solid wastes are independent of their compositions.

Table 4.3.48: CF_{RD} factors with the world as reference region (Guinée *et al.* (2001)) and newly developed factors with Australia as reference region (Data Ref. b[illegible]).

Substance	Reference Region	
	World	Australian
Black Coal	0.0134	5.28×10^{-5}
Brown Coal	6.71×10^{-3}	1.59×10^{-5}
Natural Gas	0.0245	0.0226
Oil	0.0201	0.544
Combusted Oil	0.0201	0.544
Uncombusted Oil	0.0201	0.544
Condensate	0.0201	0.459
LPG	0.0245	0.406
Petrol	0.0201	0.544
Diesel	0.0201	0.544
Fuel Oil	0.0201	0.544

photochemical oxidant formation, solid waste generation, and abiotic depletion (Burgess (1999), Golonka and Brennan (1996)). However, these factors are not relevant for the base year of 1999. Thus, the estimation of new normalisation factors for Australia is necessary.

Production of normalisation factors for Australia requires the collection of the material requirements and emissions of all human activities in Australia for one year (see Section A1.9, Appendix 1). The conversion of this data into normalisation factors requires the use of the classification and characterisation steps of LCIA (see Section 3.2.3.5, Chapter 3). The characterisation step (i.e. Equation 3.2.4, Chapter 3) should use the same CF factors for both the system environmental indicators and the normalisation factors.

Table 4.3.49 shows the estimated normalisation factors for some indicators. Lack of comprehensive Australia data precludes the estimation of normalisation factors for the remaining indicators.

4.3.6.3 ECONOMIC FACTORS

4.3.6.3.1 Factors to Produce System Economic Flows

To produce factors to convert between subsystem and system bases requires a similar process as for material flows. Unlike material flows, the economic data are correlations

Table 4.3.49: Australian normalisation factors for some environmental impacts. Factors are indicators of the environmental impacts due to all sources within Australia.

Indicator	Type	Value	
Resource Depletion	World	4.80×10^{9}	kg Sb per year
	Australian	4.04×10^{10}	kg Sb per year
	Energy Depletion	4.82×10^{12}	MJ per year
	Exergy Destruction	8.78×10^{12}	MJ per year
Climate Change		4.78×10^{11}	kg $CO_{2\text{-e}}$ per year
Eutrophication		3.44×10^{8}	kg $PO_4^{3-}{}_{\text{-e}}$ per year
Acidification		3.47×10^{9}	kg $SO_{2\text{-e}}$ per year
Photochemical Smog		9.88×10^{8}	kg $C_2H_{4\text{-e}}$ per year
Solid Waste		2.12×10^{10}	kg per year

(see Equations 3.3.6 and 3.3.10, Chapter 3). Thus, conversion to system basis requires knowledge of how independent variable(s) of each subsystem are dependent on the system output (see Section A2.2.2.5, Appendix 2). These factors are the same as the conversion factors for environmental indicators (Table 4.3.47), except for the NG and LNG mining subsystem factors (see Table 4.3.50). Since the economic data is pertinent for natural gas mining alone, allocation between the products of the natural mining stage is unnecessary. For an example of conversion for economic indicators, see Section A2.2.2.1 (Appendix 2).

Table 4.3.50: Factors for the mining subsystem of NG and LNG systems to convert the basis of economic flows data in Section 4.3.4 from subsystem to system. Units: subsystem output basis per GWh of electricity delivered.

Fuel	Technology	Mining
NG	ST	1.10×10^{-4}
	OCGT	1.50×10^{-4}
	CCGT	7.65×10^{-5}
LNG	ST	1.62×10^{-4}
	OCGT	2.20×10^{-4}
	CCGT	1.13×10^{-4}

Multiple users share the output of some subsystems. For example, presently the primary use of natural gas (and LNG) from mining and transport subsystems is

domestic heating and cooking (90 % by mass[§§§§]). In a slightly different case, domestic electricity generation consumes only 43 % of the black coal from mining subsystems, while exports consume the remainder (Data Ref. A1). Thus, the size of some subsystems is greater than strictly necessary for the system. Equation 4.3.48 shows how to estimate the proportion of the costs of the larger subsystem due to the electricity generation system alone (for example, see Section A2.2.2, Appendix 2).

$$\text{Costs}_{i,s} = \text{Costs}_{i,R}\,\frac{Q_{i,s}}{Q_{i,R}}$$

Equation 4.3.48

where: $\text{Costs}_{i,s}$ = the capital or operating costs for subsystem i of system s due to the electricity generation system; $\text{Costs}_{i,R}$ = the capital or operating costs for subsystem i at actual size; $Q_{i,s}$ = the capacity of subsystem i necessary for system s; and $Q_{i,R}$ = the capacity of subsystem i at actual size.

To produce the capital requirements indicator, I, using Equation 3.3.9 (Chapter 3) (for example, see Section A2.2.2.5, Appendix 2), requires equivalent life factors, λ_s (Table 4.3.51). These factors represent the relative life of subsystem s to the life of the entire system. This analysis assumes that for electricity generation systems, the life of the system is that of the generation subsystem. Most economic assessments of electricity generation assume a life of 20 to 30 years (see Section 2.4.3.4, Chapter 2). In this assessment, the system life is 30 years.

To produce the annual repayment, C_R, which represents the annual charge for using I (for example, see Section A2.2.2.5, Appendix 2), requires the real cost of capital, *i* (%), and life of loan, n (years). A common assumption is that n should equal the life of the project, N (years). N includes an allowance for construction time, which is variable depending on the scale of the system. Experience has shown that construction time is longer for coal than natural gas electricity generation plants (see for example DOE (U.S.A.) (1999)). This analysis includes economic impacts from this construction period by introducing interest during construction (IDC). IDC is the interest paid on

§§§§ This proportion is an assumption. Actual consumption of natural gas for electricity generation is often highly variable.

Table 4.3.51: Numbers of subsystems necessary during the operating life of a system (30 years). A value of greater than one implies that that subsystem's life is less than 30 years and a replacement system will be necessary at the end of its life.

Fuel	Subsystem lives for one generation subsystem life					
	Mining	Ref.	Transport	Ref.	Transmission	Ref.
BIC & BICE	2	A2	1.5 conveyors	A5	1	A12
			4 road	A6		
			2 rail	A7		
			2 ocean	A8		
BrC	1	A3	1	A9		
NG & LNG	1	A4	1 pipelines	A10		
			1 ocean	A11		

capital before its use in this period*****. Commonly accepted values for *i* are between 6 and 7 % (Data Ref. A13).

To produce the value added indicator, VA, using Equation 3.3.3 (Chapter 3) (for example, see Section A2.2.2.5, Appendix 2), requires the sales revenue (S) and the costs of materials produced upstream (F) and labour (L). Table 4.3.52 shows factors to estimate S from the outputs of each subsystem. These figures assume export of LNG and BICE to Japan. Hence, S factors for BICE and LNG systems are the average prices paid for fuels and electricity in Japan, not Australia. Factors to produce F are the factors to produce S for the preceding subsystem (i.e. the factor to produce S for the mining subsystem is the factor to produce F for the transport subsystem). Table 4.3.53 shows the L factors for each subsystem, expressed as a percentage of the subsystem's O & M costs.

4.3.6.3.2 Factors to Normalise Economic Indicators to the Australian Region

Australian normalisation factors for the economic indicators have never been reported for this purpose. However, I and VA are published as indicators of Australian economic performance, while AC and CVA may be estimated from other published values. Table 4.3.54 shows normalisation factors for the capital requirements (I or C_R), annualised costs (AC), value added (VA) and capital inclusive value added (CVA) indicators. For an example of normalisation, see Section A2.3, Appendix 2.

***** The interest rate for IDC is the cost of debt (13-14 %, Data Ref. A13).

Table 4.3.52: Factors to estimate sales revenue (S) values from subsystem outputs, for estimating value added (VA) ($ (AUD 2000), per t for mining and transport and per MWh for generation and transmission subsystems).

Fuel	Systems	Subsystems							
		Mining	Ref.	Transport	Ref.	Generation	Ref.	Transmission	Ref.
BIC	ST, IGCC	26.85	A14	40.60	A22	39.93	A28	61.18	A30
BICE	ST, IGCC	32.35	A15	59.12	A23	77.00	A29	92.18	A31
BrC	ST	5.31	A16	5.89	A24	39.93	A28	61.18	A30
	IGCC	6.95	A17	7.75	A25				
NG	ST, OCGT, CCGT	120.99	A18	165.88	A26	39.93	A28	61.18	A30
LNG	ST	17.39	A19	342.12	A27	77.00	A29	92.18	A31
	OCGT	18.62	A20						
	CCGT	16.06	A21						

Table 4.3.53: Labour factors (L) for estimating value added (VA). L expressed as a percentage of operating and maintenance costs (O & M).

Fuel	Systems	Subsystems							
		Mining	Ref.	Transport	Ref.	Generation	Ref.	Transmission	Ref.
BIC	ST	56.80	A32	18.28	A37	42.1	A42	10.0	A49
	IGCC					48.7	A43		
BICE	ST	49.85	A33	38.29	A38	42.1	A42		
	IGCC					48.7	A43		
BrC	ST	66.10	A34	0.00	A39	74.6	A44		
	IGCC					36.8	A45		
NG	ST	25.89	A35	18.50	A40	18.3	A46		
	OCGT					44.4	A47		
	CCGT					33.3	A48		
LNG	ST	28.92	A36	12.12	A41	18.3	A46		
	OCGT					44.4	A47		
	CCGT					33.3	A48		

Table 4.3.54: Australian normalisation factors for economic impacts. Factors are indicators of the economic impacts due to all sources within Australia.

Indicator	Factor ($ billion (AUD 2000) per year)	Ref.
I or CR	44.9	B1
AC	1070	B2
VA	169	B3
CVA	124	B4

4.3.6.4 SOCIAL FACTORS

4.3.6.4.1 Factors to Produce System Social Flows

The conversion factors for economic flows (Table 4.3.47 and Table 4.3.50) apply for social flows (for example, see Section A2.2.3.2, Appendix 2).

To produce the indirect employment (EI) indicator, using Equation 3.4.2 (Chapter 3) (for example, see Section A2.3.3.1, Appendix 2), requires industry classifications and EM factors (see Table 4.3.55). The EI indicator values use Type 2A factors, as they are the most complete measures of indirect employment (see Section 3.4.2, Chapter 3).

Table 4.3.55: Employment multipliers (EM) to estimate the value of the indirect employment (EI) indicator from direct employment (ED) (ABS (2001b)). Gen. and Trans. = Generation and Transmission.

Industry Classification	Fuel	Subsystem	EM Factors			
			1A	1B	2A	2B
Coal; oil and gas	All	Mining	2.451	3.702	7.46	6.46
Electricity	All	Gen. and Trans.	1.645	2.322	4.275	3.275
Road transport	BIC, BICE	Transport (Road)	1.441	1.745	2.698	1.698
Rail, pipeline,	BIC, BICE	Transport (Rail)	1.302	1.614	2.949	1.949
other transport	NG, LNG	Transport (Pipeline)	1.561	1.979	3.396	2.396
Water transport	LNG, BICE	Transport (Ocean)	1.706	2.239	3.639	2.639

4.3.6.4.2 Factors to Normalise Social Indicators to the Australian Region

Australian regional normalisation factors for social indicators have never been reported for this purpose. However, Australian employment (as an indicator of economic performance), LTI and fatalities (as indicators of workplace safety) have been reported separately. Table 4.3.56 shows normalisation factors for the employment (ED and EI), lost time injuries (LTI) and fatalities (Fatal) indicators. For an example of normalisation, see Section A2.3, Appendix 2.

4.3.6.5 SUMMARY OF CONVERSIONS NECESSARY TO PRODUCE INDICATORS

The conversion factors presented allow the presentation of the data collected in Sections 4.3.2 to 4.3.4 as on a system output basis, e.g. per MWh of electricity delivered. Furthermore, this section provides factors necessary to produce sustainability indicators

Table 4.3.56: Australian normalisation factors for social impacts. Factors are indicators of the social impacts due to all sources within Australia.

Indicator	Factor	Ref.
ED and EI	8.92×10^6	B1
LTI	1.54×10^5	B2
Fatal	372	B3

for each of the electricity generation systems, using the methods presented in Chapter 3.

4.3.7 SUMMARY OF ELECTRICITY GENERATION SYSTEMS AND DATA

The descriptions presented define the electricity generation systems, which consume Australian fossil fuels. The data collected and conversions described enable the production of sustainability indicators for electricity generation systems, which consume Australian fossil fuels. The basis for indicators is 1 MWh of electricity delivered to the electricity distribution network.

4.4 APPLICATION OF UNCERTAINTY AND SENSITIVITY ANALYSES

4.4.1 OVERVIEW OF THE APPLICATION OF UNCERTAINTY AND SENSITIVITY ANALYSES

The production of indicators of uncertainty requires the collection and manipulation of a broad range of data. Much of this data is either an average of data from many sources, or an average over a period (usually 1 year). The range of values combined to obtain these data averages may be considerable. It is possible that one or many of these source values are as probable as the data average to be an accurate representation of the 'true' average. Thus, the value of the data average is uncertain. Moreover, data collection relies on a number of assumptions that may not be accurate. Data uncertainty and poor assumptions may influence the accuracy of the collected data and, consequently, the indicators. Section 3.3.3.4 (Chapter 3) discusses methods for assessing the affect of these uncertainties. This section examines how to apply two of these methods, uncertainty and sensitivity analysis, to this sustainability assessment of electricity generation systems.

Section 4.4.2 discusses the application of uncertainty analysis to estimate uncertainties caused by the data collected in Section 4.3. Section 4.4.3 discusses the application of sensitivity analysis to estimate uncertainties caused by assumptions in Section 4.3.

4.4.2 APPLICATION OF UNCERTAINTY ANALYSIS

Uncertainty analysis involves the estimation of the range of outcomes possible from the LCA based on variability in the data used to construct the study. In general, an uncertainty analysis will determine the variability of the impact assessment scores generated based on the individual variability of input data. Others have acknowledged the wide range of uncertainty in supply chains for electricity generation systems as a difficulty in assessment of their sustainability (IAEA (2000)). Thus, this analysis tests methods developed for use in LCA, all appearing in Section 3.2.3.7 (Chapter 3). Time and resource constraints limit the analysis to the brown coal and black coal steam turbine systems (ST-BrC and ST-BlC). These same constraints required the use of 'rules of thumb' to estimate ranges for some data. The quantitative and qualitative data necessary for the uncertainty assessment appears in Appendix 1.

4.4.3 APPLICATION OF SENSITIVITY ANALYSIS

Sensitivity analysis tests the influence of decisions made in sustainability assessment on the indicator values. Some key decisions in data collection include the:

- methods used to allocate material flows in natural gas and black coal mining;
- assumed distances for LNG and export black coal (BlCE) transport;
- electrical generation efficiencies of the generation subsystems; and
- chosen system capacity in the economic and social indicator methods.

Section 4.3.6.2.1 details an allocation method for natural gas mining based on relative fuel gas consumption. This same section assumes no allocation necessary for the black coal mining. Commonly, the basis for allocation is the relative economic values of the subsystems' products. Table 4.4.1 shows the product of allocation and conversion factors obtained when using an economic basis for allocation (see Section

Table 4.4.1: Factors for natural gas and black coal mining to convert from subsystem to system basis when using the economic allocation method. Units: subsystem output basis per GWh of electricity delivered.

Fuel	Technology	Mining	Ref.
BlC	ST	4.56×10^{4}	A1
	IGCC	2.56×10^{4}	A2
BlCE	ST	6.72×10^{4}	A3
	IGCC	3.77×10^{4}	A4
NG	ST	1.12×10^{4}	A5
	OCGT	1.52×10^{4}	A6
	CCGT	7.77×10^{3}	A7
LNG	ST	8.83×10^{5}	A8
	OCGT	1.20×10^{4}	A9
	CCGT	6.15×10^{3}	A10

A2.2.1.2, Appendix 2). The sensitivity analysis compares the indicators produced using economic value and the original bases for allocation.

The transport distance for LNG and export black coal (BlCE) assumes that the destination in Japan. However, the U.S.A. has also been a destination for Australian LNG (13500 km), and Europe is a common destination for BlCE (21500 km). The sensitivity analysis compares the indicators produced using these and the original distances.

The electrical generation efficiency dictates the amount of fuel necessary for the generation subsystems. The data collection methodology adopted ensures that the data in Section 4.3 refers to generation subsystems with Australian average electrical efficiencies. However, Section 4.3 acknowledges that in practice a range of electrical efficiencies occurs, due to differences in operation, age, and minor improvements (see Table 4.4.2). The sensitivity analysis compares the indicators produced using the minimum, maximum and original electrical efficiencies.

The method for producing economic indicators assumes a system capacity of 1000 MW delivered (see Section 4.3.6.3.1). This capacity represents neither a large nor a small capacity system. In Australia, capacities range from, below 100 MW for some NG-OCGT systems, to over 2000 MW for some BlC-ST systems. The sensitivity analysis compares indicators assuming capacities of 500 MW and 2000 MW with the indicators assuming a capacity of 1000 MW.

Table 4.4.2: Minimum, average and maximum electrical generation efficiencies of generation subsystems. Also shown are multipliers (upstream factors) to estimate the additional impacts for minimum and maximum efficiencies (multiply each conversion factor of Table 4.3.47 by the upstream factor).

Fuel	Technology	Efficiencies			Upstream Factor		
		Min.	Ave.	Max.	Min.	Ave.	Max.
BlC and BlCT	ST	30	33	37	1.11	1.00	0.902
	IGCC	40	51	52	1.26	1.00	0.997
BrC	ST	21	27	28	1.16	1.00	0.895
	IGCC	40	48	48	1.19	1.00	1.00
NG and LNG	ST	30	35	35	1.17	1.00	1.00
	OCGT	17	26	37	1.51	1.00	0.694
	CCGT	44	50	57	1.14	1.00	0.881

4.4.4 Summary of the Application of Uncertainty and Sensitivity Analyses

The assumptions and decision points identified have most influence on the uncertainty of the environmental indicators of sustainability for the electricity generation system. Uncertainty analysis and sensitivity analysis allow the estimation of the influence of this uncertainty on the sustainability indicator results. This section establishes several probable choices for each assumption or decision point in the electricity generation systems. This information will allow the analysis of the uncertainty and sensitivity of the sustainability indicators.

4.5 SUMMARY OF ELECTRICITY GENERATION SYSTEMS AND DATA

Each of the electricity generation systems this chapter describes is important in current and future electricity generation using Australian fossil fuels. Material, economic and social flows data for these systems, in conjunction with given conversion factors and the methods Chapter 3 presents, will allow the production of indicators of environmental, economic and social sustainability for the electricity generation systems.

This chapter selects the brown coal and black coal steam turbine (BrC-ST and BlC-ST) systems for testing some promising uncertainty techniques. Additionally, it identifies assumptions and decisions having potentially great influence on the accuracy of the results for a sensitivity analysis.

5. RESULTS OF THE SUSTAINABILITY ASSESSMENT

5.1 OVERVIEW OF RESULTS OF THE SUSTAINABILITY ASSESSMENT

The preceding chapters present methods (Chapter 3) and information (Chapter 4) for the production of indicators of sustainability for electricity generation systems, which consume Australian fossil fuels. Additionally, these chapters include methods for estimating the uncertainty of these indicators due to uncertainties in the data and the sensitivity of the indicators to assumptions. Consequently, with this information it is possible to produce indicators of the sustainability for these systems and test their robustness to data uncertainties and assumptions.

Section 5.2, contains environmental indicators for the electricity generation systems, and results of data quality and sensitivity analyses. Similarly, Sections 5.3 and 5.4 contain economic and social indicators for these systems, and results of a sensitivity analysis. Section 5.5 combines the environmental, economic and social indicators using normalisation.

5.2 ENVIRONMENTAL INDICATOR RESULTS

5.2.1 Overview of Environmental Indicator Results

Environmental indicators are one type of indicator of sustainability. They provide simple measures of the effect of material consumption and emissions on the environment. This section presents environmental indicators of sustainability for each of the electricity generation systems.

Section 5.2.2 presents environmental indicators for each electricity generation system. Each of these systems has four subsystems: fuel mining; fuel transport;

electricity generation and electricity transmission. Section 5.2.2 also presents estimates of each of these subsystems contribution to the system indicators. Sections 5.2.4 and 5.2.5 present the results of the sensitivity and uncertainty analyses, which estimate the affect of data uncertainty and value-based decisions on the indicators.

5.2.2 SYSTEM INDICATOR SCORES

Sections 4.3.2 to 4.3.6 (Chapter 4) contain the data required to produce the environmental indicators. Sections 4.3.2 to 4.3.4 contain this data on a subsystem basis, and Section 4.3.6 contains factors for its conversion to system basis (Chapter 4). Equation 3.2.4 allows production of the indicators from this data (see Section 3.2.3.5, Chapter 3). Equation 3.2.4 requires the CF factors of Section 4.3.6.2.2 (Chapter 4) for each environmental indicator. The environmental indicators produced using this method appear in Table 5.2.1.

5.2.3 OBSERVATIONS FROM THE INDICATORS

5.2.3.1 CLIMATE CHANGE (CC)

Of the systems, ST-BrC have the worst CC indicator scores (1210 kg $CO_{2\text{-eq}}$ per MWh delivered), due to their relatively low electricity generation efficiency, derived from the fuel's high moisture content, and the high carbon to hydrogen ratio of the brown coal fuel (see Figure 4.3.4, Chapter 4). Predictably the next two worst systems are also low efficiency, coal fuelled processes, ST-BICE (1110) and ST-BIC (1060). The transport distance of the export system (ST-BICE) is greater than the domestic case, so its indicator score is worse (ST-BIC). The system in fourth position is a natural gas fuelled system, OCGT-LNG, due to its low efficiency. Its indicator score (1050) is similar to that of the ST-BIC system, and worse than the BIC- and IGCC-BICE systems. This evidence supports the claim that CC scores for natural gas systems can be worse than a black coal system (see Section 1.1, Chapter 1). In contrast, the combination of high efficiency and lower carbon to hydrogen ratio of the natural gas based fuels (see Figure 4.3.4, Chapter 4) ensures that the CCGT-NG (458) and CCGT-LNG (566) systems have the best indicator scores. This evidence supports the claim that CC scores for natural gas systems can be better than coal systems (see Section 1.1, Chapter 1).

Table 5.2.1: Environmental indicators for electricity generation from Australian fossil fuels (CC = climate change (kg $CO_{2\text{-eq}}$), AD = acidification (kg $SO_{2\text{-eq}}$), EU = eutrophication (kg $PO_4^{3-}{}_{\text{-eq}}$), PS = photochemical smog (kg $C_2H_{4\text{-e}}$), HT and ET = human and eco-toxicity (kg 1,4-dichlorobenzene), PM and SW = particulates and solid waste emissions (kg), WD = water consumption (t), RD A and RD W = Australian and world resource depletion (kg $Sb_{\text{-e}}$), EN and EX = energy consumption and exergy destruction (GJ), all per MWh of electricity delivered).

Fuel	Tech.	Indicator												
		CC	AD	EU	PS	HT	ET	PM	SW	WD	RD A	RD W	EN	EX
BIC	ST	1060	6.68	0.437	0.314	5270	4.9	0.548	87.3	2.37	0.774	6.29	11.3	13.7
	IGCC	683	0.171	0.0261	0.0193	74.6	0.289	0.038	63	1.3	0.542	3.71	6.55	8.26
BICE	ST	1110	7.34	0.459	0.35	5830	5.92	1.05	310	2.65	5.73	9.49	17.1	20.6
	IGCC	709	0.577	0.0588	0.0457	370	0.842	0.315	187	1.45	3.14	5.48	9.75	12.3
BrC	ST	1210	3.13	0.218	0.148	2410	2.62	0.493	21.8	2.68	0.185	9.83	13.9	12.4
	IGCC	750	2.41	0.0244	0.105	2430	0.44	0.0218	13.7	0.657	0.244	5.26	7.42	6.85
NG	ST	724	0.944	0.236	0.158	42.2	2.21	0.035	0.0213	139	5.54	5.58	6.9	11.9
	OCGT	847	1.47	0.368	0.228	60.9	3.64	0.285	0.0282	0.00	7.59	7.46	9.24	15.9
	CCGT	458	0.415	0.0998	0.0982	33.6	0.965	0.0372	0.0148	25.2	3.98	3.91	4.85	8.39
LNG	ST	878	1.44	0.333	0.369	177	3.16	0.0714	0.0711	144	11.1	6.45	8.15	13.8
	OCGT	1050	2.14	0.499	0.511	241	4.91	0.335	0.0948	5.13	15	8.63	10.9	18.4
	CCGT	566	0.764	0.168	0.246	128	1.62	0.0627	0.0497	27.9	7.84	4.52	5.72	9.7

5.2.3.2 ACIDIFICATION (AD)

Black coal systems have the worst AD indicator scores, ST-BICE (7.34 kg $SO_{2\text{-eq}}$ per MWh delivered), and ST-BIC (6.69). Emissions of SO_2 and NO_x are the major contributors to the AD indicator scores. BIC has higher proportion of sulfur than the other fuels (see Figure 4.3.4, Chapter 4), which during its combustion (in the generation subsystem) becomes SO_2. The score of the ST-BICE system is worse than in many operating systems, which often treat flue gas to reduce SO_2 emissions. Contrariwise, the IGCC-BIC system has the best AD score (0.171). This system removes almost all sulfur from the flue gas (>98 %). Without removing sulfur, its score would be third worst (4.50). Similarly, without sulfur removal, the ST-BICE system is worse than the ST-BIC system. The scores for the brown coal system's are approximately half those of equivalent black coal fuelled systems. This reflects the much lower sulfur content in brown coal (see Figure 4.3.4, Chapter 4). All natural gas fuelled systems have relatively low AD scores (up to 2.12), as the sulfur content of raw natural gas is minimal in Australia (see Figure 4.3.4, Chapter 4). AD scores for natural gas systems are mainly due to nitrogen oxides (NO_x), which are less powerful acidifying gases per unit mass than SO_2.

5.2.3.3 *EUTROPHICATION (EU)*

The OCGT-LNG (0.499 kg $PO_{4\text{-eq}}$ per MWh delivered), ST-BICE (0.459), and ST-BIC (0.437) have worst EU scores, due to their relatively high NO_x production. Importantly, the systems whose electricity generation technology has stringent NO_x controls (IGCC and CCGT) have the best scores (i.e. IGCC-BrC (0.0244) and IGCC-BIC (0.0260)). The ST-BrC system has lower NO_x levels than the ST-BIC system, due to its lower flame temperature (see Section 4.3.3.3.1, Chapter 4). Consequently, its EU scores (0.218) is better. NG and LNG systems have similar scores to the coal systems, as, while their fuel contains less nitrogen, they have higher flame temperatures, resulting in similar levels of NO_x emissions.

5.2.3.4 *PHOTOCHEMICAL SMOG (PS)*

The LNG based systems, OCGT-LNG (0.511 kg $C_2H_{4\text{-eq}}$ per MWh delivered) and ST-LNG (0.369), have worst scores, due to substantial NO_x production in the transport subsystem. This subsystem includes LNG production subsystem, which consumes a low hydrocarbon and high nitrogen content fuel gas to provide energy for the intensive liquefaction process. These NO_x emissions from the LNG production subsystem are also important contributors to the poor LNG scores for AD, EU, HT and ET. Fugitive hydrocarbon releases, while included in the assessment, made minimal contribution to this impact.

5.2.3.5 *HUMAN (HT) AND ECO-TOXICITY (ET)*

The indicator scores for HT and ET show NG and LNG systems to have lowest toxicity, while BIC- and ST-BICE have worst toxicity. These scores have limited value as they include only a limited range of substances (H_2S, NO_x, SO_2, N_2O and particulates) (see Section 4.3.5, Chapter 4). Of these, SO_2 has the greatest influence on the indicator

scores. Thus, the BIC- and IGCC-BICE systems, with sulfur removal, have substantially better scores than the BIC- and ST-BICE systems, without sulfur removal.

5.2.3.6 *PARTICULATES (PM)*

The PM scores of the coal systems are substantially worse than for gas systems, with the greatest impact, ST-BICE (1.05 kg particulates per MWh delivered), corresponding to the system requiring the greatest amount of coal handling operations (4, including all stockpiles and transfers during transport). The second largest score, ST-BIC, entails half as many handling operations for a similar coal requirement. Its score (0.548) is approximately half that of the ST-BICE system. This indicates that limiting transfers will reduce black coal PM scores. The brown coal systems have somewhat lower the particulate emissions from coal handling than do black coal systems, due mainly to the high coal moisture content (see Figure 4.3.4, Chapter 4). However, their PM scores are still high (ST-BrC 0.493), because of emissions from their combustion in the generation subsystem. PM scores for the ST-NG, IGCC-BrC, IGCC-BIC, and the CCGT-NG systems are all minimal (0.022-0.038).

5.2.3.7 *SOLID WASTE (SW)*

SW indicator scores for the coal systems are far worse than are the scores of the natural gas systems. The major contributors to PM are waste coal (from coal cleaning operations), ash (from coal combustion), and ash/limestone mixtures (from in-bed desulfurisation operations). The greatest scores are for the export black coal systems, ST-BICE (310 kg solid waste per MWh delivered) and IGCC-BICE, as only these systems produce both waste coal and coal-ash mixtures. The domestic black coal systems are next, which produce either ash (ST-BIC 87.3) or ash/limestone mixtures (IGCC-BIC 63.0). The very low ash content of the brown coal (approximately 0.9 % by mass, c.f. black coal 8-25 % by mass, see Figure 4.3.4, Chapter 4) ensures that despite its greater mass consumption, the SW scores (ST-BrC 21.8, IGCC-BrC 13.7) are much lower than equivalent black coal systems. Overburden, the non-coal material removed to mine coal, is not included in SW, as mining generally returns this material continuously or in the rehabilitation phase (see Chapter 4). Inclusion of overburden would accentuate the differences between the coal and gas systems. Moreover, as the overburden produced in BlC systems is 4-5 times that of BrC systems, inclusion would accentuate the differences between black and brown coal systems.

5.2.3.8 *Water Depletion (WD)*

WD scores for all NG and LNG systems, except OCGT systems, are substantially greater than BlC and BrC systems. These systems, in all Australian cases, use once-through cooling water for condensers in the generation subsystem, and for the LNG case, in the LNG vaporisation step of the transport subsystem. While the treatment of some of this water with chemicals, such as chlorine, does occur, the average chemical composition of the water discharged is unchanged. The main consequence is an increase in temperature of this water by up to 8 °C. The water consumption of BrC and BlC plants assumes the use of circulating cooling water for condensers. These systems use considerably less water, but wastewater from these systems requires treatment to remove contaminants before discharge. Much of the water consumed for circulating systems is lost through evaporation in cooling towers.

5.2.3.9 *Resource Depletion (RD A and RD W), Energy Depletion (EN) and Exergy Destruction (EX)*

RD A, RD W, EN and EX are all indicators of the impact on sustainability caused by consuming natural resources. The ST-BlCE (17100 MJ energy per MWh delivered), ST-BrC (13900), ST-BlC (11300), and OCGT-LNG (10900) systems have worst EN indicator scores. Yet, for the EX indicator, the order is different: ST-BlCE (20600 MJ exergy per MWh delivered), OCGT-LNG (18400), OCGT-NG (15900), and ST-LNG (11900). The order changes because the combustion of liquid transport fuels (such as fuel oil and diesel) and natural gas destroys greater exergy than an equivalent amount of the coal fuels. The ST-BlCE system uses considerable amounts of diesel in both the mining and transport subsystems. The LNG and NG systems consume natural gas in the mining, transport and generation subsystems. The ST-BrC (9.83 kg Sb_{-eq} per MWh delivered), ST-BlCE (9.49), and OCGT-LNG (8.63) systems have the worst RD W indicator scores. In contrast, the NG and LNG systems have the worst RD A indicator scores (i.e. OCGT-LNG 15.0 kg Sb_{-eq} per MWh delivered, ST-LNG 11.1, and CCGT-LNG 7.84).

5.2.3.10 *All Indicators*

No single electricity generation system has the worst score for every indicator. However, the CCGT-NG systems have the best scores in many categories. The ST-BrC system has the greatest indicator score for CC, but is not the worst contributor to any other indicator, except RD W. Thus, BrC is not the worst environmental performer. Therefore, these results do not support claims to the contrary, like the quote at the beginning of Chapter 1. The advanced coal generation technology, IGGC, improves significantly the indicator scores of both the BrC and BlC systems from their respective ST systems. However, the AD and SW indicator scores of the IGCC-BlC system are still poor in comparison with systems consuming BrC and NG. The indicators scores for LNG systems are generally better than for those of BlCE systems, except in indicators where NO_x emissions are important contributors (i.e. AD, PS, EU).

5.2.3.11 *Subsystem Contributions*

Each of the fossil fuel and technology combinations for electricity generation from Australian fossil fuels contains four subsystems. Figure 5.2.1 shows the contribution of each subsystem to the total environmental indicator magnitude for each combination.

Contributions of the non-generation subsystems are considerable for many of the indicators. The contribution of mining to the indicators of natural gas systems is uniformly greater than the contributions of mining to the indicators of the coal systems. The contributions of the mining and transport subsystems for LNG systems are even greater than the natural gas systems, due to the considerable energy requirements of liquefaction of natural gas, and lengthy ocean transport of LNG. The transport subsystem of IGCC-BlCE systems contributes highly in many categories (AD, EU, PS, HT, ET, PM) due mainly to the relatively low generation emissions of these systems. The contributions of the transport subsystems to RD A for the BlCE and LNG systems are also considerable.

5.2.4 Uncertainty Analysis

5.2.4.1 *Overview of Uncertainty Analysis*

This section contains a data quality analysis of the ST-BlC and ST-BrC systems. The

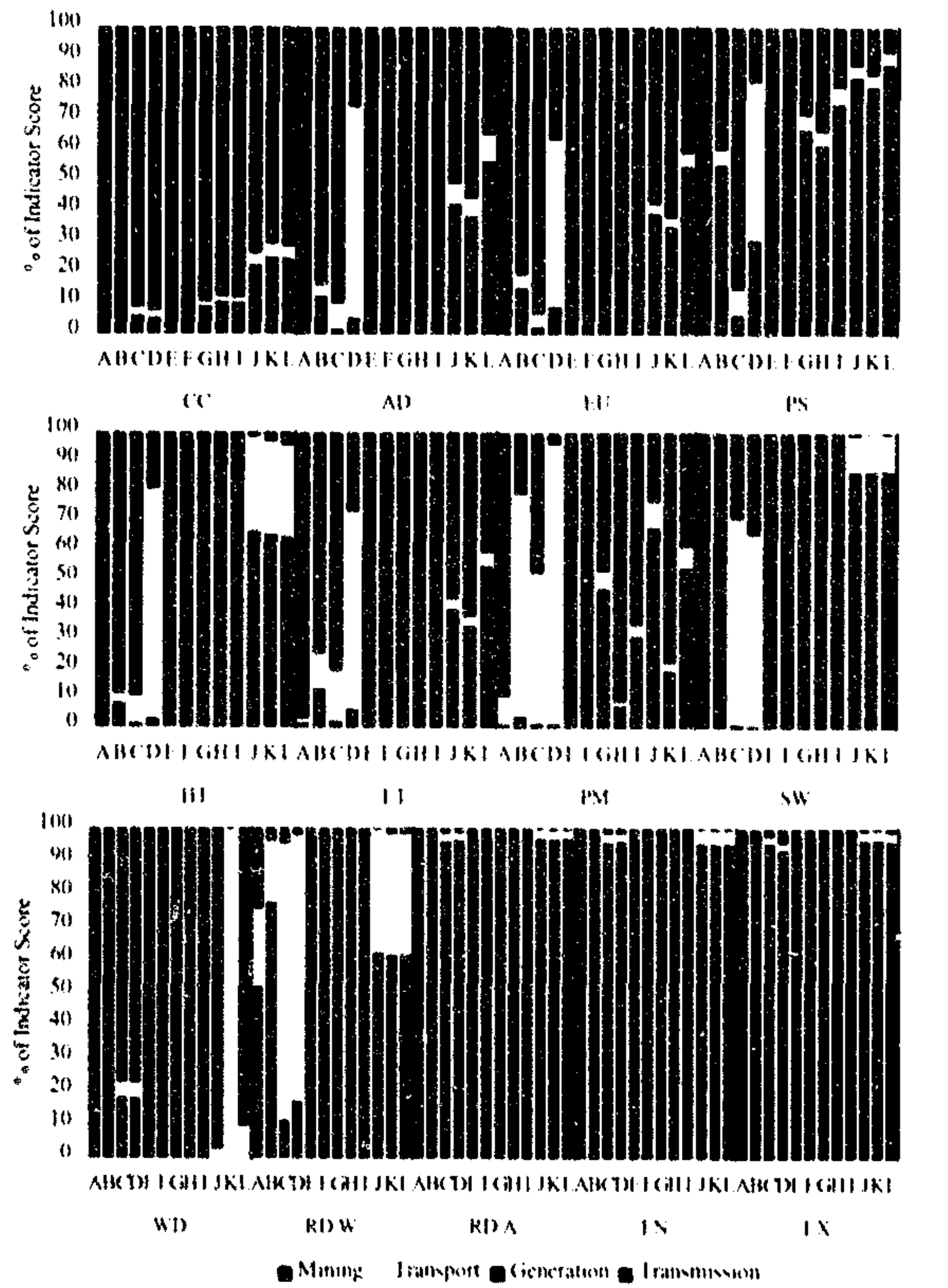

Figure 5.2.1: Subsystem contributions to the environmental indicators for electricity generation from Australian fossil fuels (A = ST-BlC, B = IGCC-BlC, C = ST-BlCE, D = IGCC-BlCE, E = ST-BrC, F = IGCC-BrC, G = ST-NG, H = OCGT-NG, I = CCGT-NG, J = ST-LNG, K = OCGT-LNG, and L = CCGT-LNG). Tabulated subsystem contributions appear in Section A3.2 (Appendix 3).

presentation is in the same order as the discussions of data quality analysis methods in Section 3.2.3.7 (Chapter 3). Thus, Section 5.2.4.2 includes results using numerical methods, Section 5.2.4.3 qualitative methods, Section 5.2.4.4 combined methods, and Section 5.2.4.5 comparisons.

5.2.4.2 NUMERICAL UNCERTAINTY

Estimating numerical uncertainty uses Monte-Carlo simulations for both black and brown coal cases (see Section 3.2.3.7.2, Chapter 3). Varied in the simulations are all data necessary to produce the CC, AD and RD W indicators, except the CF factors. Each simulation involved 10000 calculations of each of these indicators, using XlSim' software. As many data point's uncertainty distributions are unknown, a number of common types are tested: triangular, uniform, normal and log normal (see Figure 3.2.2, Chapter 3). The basis for these distributions is the indicator's maximum, minimum and mean values. The effect of this choice is considerable (see Table 5.2.2). The minimum mean value and standard deviation occur when using normal distributions, and the maximum standard deviations occur when using uniform distributions. In the calculation of the AD potential of the brown coal system the use of triangular and uniform distributions worsens the mean indicator value by over 300 %.

Table 5.2.2: Estimates of the uncertainty of some environmental indicators from the use of Monte-Carlo simulation (SD = standard deviation).

	Probability Distribution Type	CC (kg_{CO_2-eq} per MWh) Mean	CC SD	AD (kg_{SO_2-eq} per MWh) Mean	AD SD	RD W (kg[illegible] per MWh) Mean	RD W SD
Black Coal	Average	1040	-	6.77	-	6.37	-
	Triangular	1082	309	7.98	2.90	6.51	1.92
	Uniform	1080	460	9.32	4.53	4.55	2.89
	Normal	1038	255	6.88	2.21	6.40	1.53
	Log Normal	1099	334	7.38	2.83	6.79	2.16
Brown Coal	Average	1341	-	3.47	-	10.9	-
	Triangular	1319	102	12.0	6.1	11.1	0.6
	Uniform	1386	138	19.3	8.2	11.3	0.9
	Normal	1338	76	3.34	4.67	10.9	0.5
	Log Normal	1346	76	4.92	3.38	10.9	0.5

Some additional simulations determine which data are the greatest contributors to the final uncertainty profile (see Table 5.2.3). These simulations remove the uncertainty

Table 5.2.3: Simulations using Monte-Carlo simulation to indicate the influence of individual data uncertainty on indicator uncertainty (Triangular distribution, SD = standard deviation), A from Table 5.2.2.

Parameter held constant	CC (kg_{CO_2-e} per MWh)			
	Black Coal		Brown Coal	
	Mean	SD	Mean	SD
No Variable Fix [A]	1082	309	1319	102
Power Station Efficiency	1084	65	1368	59
Coal Lost in Transit	1111	277	1382	101
Coal CO2 Emission Factor	1055	304	1363	80
Coal-Bed Methane	1085	298	1319	102

profile for a chosen data point, and thus hold the chosen data point constant in all simulations. Holding the power station efficiency constant substantially reduces the standard deviations and therefore the variability of the results. It also makes the uncertainty ranges of the black and brown coal systems similar. In the brown coal case, the variation due to uncertainty in the emission factor of CO_2 from coal combustion is also a significant contributor. Other data uncertainties, such as the amount of coal lost as dust in mining and transportation, and coal-bed methane emission factor, are minor contributors to the uncertainty of the results.

5.2.4.3 *QUALITATIVE UNCERTAINTY*

Qualitative uncertainty measures for the black and brown coal systems use a single set of indicators (Table 3.2.3, Chapter 3) to ensure a fair comparison. These indicators are all data level indicators, while both methods include process and system level indicators in their intended indicator sets.

Table 5.2.4 shows the qualitative uncertainties calculated using the method of Wrisberg (see Section 3.2.3.7.3, Chapter 3). Aggregation is for each subsystem independently as well as for the total system to highlight the areas in which quality is poorest (i.e. has highest score). Reliability and completeness are the major contributors to qualitative error for both black and brown coal cases. Addition of the '%' column shows the relative contributions of each subsystem to the total indicator. Thus, as the transmission data indicators contribute less than 10 % to the totals, increases in the quality of the transmission data will not substantially decrease the totals. Mining and transport contributed higher than expected proportions to the totals.

Table 5.2.4: Qualitative uncertainty scores for the data of the ST-BIC and ST-BIC systems calculated using the Wrisberg method (Min. = Mining, Tsp. = Transport, Gen. = Generation and Trm. = Transmission).

Sub-system	Score									
	Reliability		Completeness		Temporal		Geographical		Technological	
	Score	%	Score	%	Score	%	Score	%	Score	%
Black Coal										
Min.	2.87	35	3.60	40	1.20	29	1.60	39	1.67	42
Tsp.	3.57	20	4.14	21	2.14	24	1.71	20	1.29	15
Gen.	2.47	38	2.26	32	1.37	41	1.21	38	1.26	40
Trm.	4.00	7	5.00	7	2.00	6	1.00	3	1.00	3
Total	2.86	100	3.16	100	1.47	100	1.42	100	1.40	100
Brown Coal										
Min.	2.82	32	2.64	26	1.00	19	1.18	25	1.36	31
Tsp.	3.83	23	4.00	21	3.00	32	2.00	23	1.00	12
Gen.	1.64	37	2.23	44	1.09	42	1.14	48	1.18	53
Trm.	4.00	8	5.00	9	2.00	7	1.00	4	1.00	4
Total	2.39	100	2.73	100	1.39	100	1.27	100	1.20	100

Table 5.2.5 shows the total qualitative uncertainties calculated using the method of Rousseaux *et al.* (see Section 3.2.3.7.3, Chapter 3). When a target quality score of 1 or 2 is set, the acceptability (i.e. the percentage of inventory scores equal to the target score or less) for each indicator is lower for black coal than brown coal. This indicates that the data quality of the brown coal system is better than for the black coal system. Comparing variability scores, it is noticeable that both systems have high temporal scores.

Table 5.2.5: Qualitative uncertainty scores for the data of the ST-BIC and ST-BIC systems calculated using the Rousseaux *et al.* method.

Indicator	Acceptability at Objective Quality Score				Variability
	1	2	3	4	
Black Coal					
Reliability	0.0	51.2	76.7	86.0	40.9
Completeness	0.0	48.8	62.8	72.1	54.1
Temporal	79.1	86.0	93.0	95.3	75.9
Geographical	74.4	86.0	97.7	100	44.4
Technological	81.4	81.4	97.7	100	51.7
Brown Coal					
Reliability	36.6	61.0	73.2	90.2	81.3
Completeness	2.4	68.3	78.0	78.0	58.6
Temporal	85.4	90.2	92.7	92.7	85.9
Geographical	80.5	92.7	100	100	27.7

Technological	90.2	90.2	100	100	30.2

5.2.4.4 COMBINED UNCERTAINTY

The combined uncertainty measures for the black and brown coal systems use the methods of Kennedy *et al.* and Meier, and the indicators shown in Table 3.2.3 (Chapter 3). Presented in Table 5.2.6 are CC indicator uncertainties, along with the numerical simulation results reported in Table 5.2.2. For the black coal system, the use of the Kennedy *et al.* method modified the mean value by a small amount (± 5 %), while increasing the standard deviation (and hence uncertainty) by 40-90 %. The use of the Meier method has little effect on either the mean or the standard deviation. For the brown coal system, both methods left the mean unchanged, while increasing the standard deviation dramatically. In fact, the standard deviations of the Kennedy *et al.* brown coal systems are very similar to those of the black coal system, although still lower as a percentage of the mean values. Therefore, it is clear that the brown coal system has lower uncertainty than the black coal system.

Table 5.2.6: Uncertainty in the CC indicator obtained using Monte-Carlo simulation, and the methods of Kennedy at al. and Meier (SD = Standard Deviation).

Distribution	Method	CC (kg_{CO_2-eq} per MWh)			
		Black Coal		Brown Coal	
		Mean	SD	Mean	SD
Triangle	Numerical	1082	309	1319	102
	Kennedy *et al.*	1062	545	1355	558
	Meier	1059	331	1367	158
Uniform	Numerical	1080	460	1386	138
	Kennedy *et al.*	1087	663	1423	550
	Meier	1108	495	1393	230
Normal	Numerical	1038	255	1338	76
	Kennedy *et al.*	1027	478	1354	551
	Meier	1021	259	1342	135
Lognormal	Numerical	1099	334	1346	76
	Kennedy *et al.*	1102	572	1331	524
	Meier	1074	332	1353	139

5.2.4.5 COMPARISONS

The differential case (brown coal system minus black coal system) (Table 5.2.7) can determine which system has least environmental impact. While the average values

indicate that the black coal system has lower CC and RD W impacts and higher AD impact, the numerical ranges overlap indicating that these outcomes are not certain.

Table 5.2.7: Uncertainty in the difference between indicators for the brown and black coal systems obtained using Monte-Carlo simulation (per MWh).

System	Probability Distribution Type	CC (kg_{CO_2-eq})		AD (kg_{SO_2-eq})		RD W (kg_{Sb-eq})	
		Mean	SD	Mean	SD	Mean	SD
ST-BlC - ST-BrC	Average	301	-	-3.30	-	4.54	-
	Triangular	237	321	4.02	6.60	4.55	2.05
	Uniform	306	484	10.0	9.2	6.77	2.8
	Normal	300	267	-3.53	5.05	4.52	1.62
	Log Normal	247	341	-2.46	4.57	4.15	2.21

Figure 5.2.2 shows a normalised difference probability distribution plot for the triangular CC impact (calculated as (brown coal-black coal)/brown coal). This shows that there is a 12 % chance that the brown coal system is at least 10 % better than the black coal system, while there is a (100-41) or 59 % chance that the black coal system is 10 % better than the brown coal system.

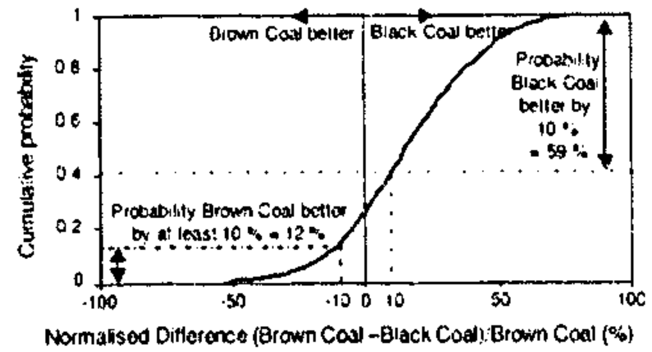

Figure 5.2.2: Cumulative distribution function of the difference between the CC indicators, obtained using Monte-Carlo simulation, of the brown and black coal systems.

5.2.5 SENSITIVITY ANALYSIS

The sensitivity analysis tests the influence of three decisions on the indicator values: allocation between products of the black coal and natural gas mining subsystems; transport distances (for LNG and BICE systems); and electricity generation efficiency.

The results of the sensitivity analysis have the same form as the main results shown in Table 5.2.1[*].

The variation of the allocation procedure for black coal mining from unallocated to economic value based allocation result in minor (less than 1 %) variations in environmental indicators. Variation of the natural gas mining allocation procedure also minimally changes the NG system environmental indicators. However, the changes to the LNG system indicators from this variation are more substantial. With economic allocation, the emission related indicators (CC, AD, EU, PS, PM and SW[†]) improve by 10-40 %, and requirement-related indicators (RD A, RD W, EN and EX) improve by 7-8 % over the base values in Section 5.2.2.

The variation of BICE transport subsystem destination from Japan to Europe worsens CC, SW, PM, AD W, EN and EX by less than 4 %, AD, PS and EU of the ST-BICE system by greater amounts, and AD, PS and EU of the IGCC-BICE system and AD A of both BICE systems by large amounts. The variation of LNG transport subsystem destination from Japan to U.S.A. worsens all indicators by less than 10 %, except for AD A, which worsens by 40 %.

Variation of the electrical generation efficiency produces considerable variation, in most cases between 85 and 115 % of the average value (for example, Table 5.2.8).

Table 5.2.8: Changes in environmental indicators when varying electrical generation efficiency as part of a sensitivity analysis (per MWh). Efficiencies appear in Table 4.4.2. EIV is ratio of the average of each indicator's percentage range and the value at the average efficiency.

System	CC (kg CO_{2-eq})		System	CC (kg CO_{2-eq})	
	EIV[*]	Range		EIV	Range
ST-BrC	90.0-115	1090-1410	ST-NG	100-111	724-736
ST-BIC	90.1-111	956-1180	ST-LNG	100-113	878-917
ST-BICE	89.2-110	987-1220	OCGT-NG	69.4-151	588-1280
IGCC-BrC	100-115	750-886	OCGT-LNG	69.3-151	731-1590
IGCC-BIC	99.7-119	681-857	CCGT-NG	88.0-114	404-523
IGCC-BICE	88.6-110	699-880	CCGT-LNG	88.0-114	499-647

[*] The full set of sensitivity results can be examined by private arrangement.

[†] See Table 5.2.1 or the nomenclature for definitions.

5.2.6 SUMMARY OF ENVIRONMENTAL INDICATOR RESULTS

The environmental indicators presented here show the major affects of electricity generation systems, using Australian fossil fuels on the environment. The subsystem breakdown establishes the proportional influence of each subsystem on the total system indicator. Comparisons of these indicators allow the ranking of each electricity generation system for environmental impact. A discussion of the results of the sensitivity and uncertainty analyses will establish the robustness of these rankings to data variability and assumptions. Chapter 6 discusses the implications of these results on the sustainability of electricity generation systems.

5.3 ECONOMIC INDICATOR RESULTS

5.3.1 OVERVIEW OF ECONOMIC INDICATOR RESULTS

Economic indicators are a second type of indicator of sustainability. They present simple measures of either the consumption or generation of money on the economy. Thus, this section presents economic indicators of sustainability for each of the electricity generation systems.

Section 5.3.2 presents the economic indicators for each electricity generation system. As with the environmental indicators (see Section 5.2), Section 5.3.2 also presents estimates of the contribution of each subsystem to the system indicators. Section 5.3.3 presents the results of the sensitivity analysis, which estimates the affect of value-based decisions on the indicators.

5.3.2 SYSTEM INDICATOR SCORES

Sections 4.3.2 to 4.3.6 (Chapter 4) contain the data required to produce economic indicators. Sections 4.3.2 to 4.3.4 contain this data on a subsystem basis, and Section 4.3.6 contains factors for its conversion to system basis (Chapter 4). System basis capital costs (I) use the λ factors of Section 4.3.6.3 in Equation 3.3.9 (Chapter 3). System annualised costs (AC) use the i and n values of Section 4.3.6.3 in Equation 3.3.8 (Chapter 3) to produce the C_R for Equation 3.3.12 (Chapter 3). The O & M in Equation 3.3.8 is the sum of the system O & M (or O) values. System value added (VA) uses the

S, L and F values of Section 4.3.6.3 in Equation 3.3.3 (Chapter 3). The system capital inclusive value added (CVA) method subtracts the system C_R values of the AC factor from the system VA values. The AC, VA and CVA indicators are indicators of wealth generation, while I is an indicator of capital expenditure. The economic indicators produced using this method appear in Table 5.3.1.

Table 5.3.1: Economic indicators for electricity generation from Australian fossil fuels (I = capital cost ($ billion (AUD 2000)), I_R, AC, VA and CVA = relative capital cost, annualised cost, value added and capital inclusive value added ($ (AUD 2000) per MWh of electricity delivered)).

Fuel	Technology	Indicator				
		I	I_R	AC	VA	CVA
BIC	ST	2.29	450	66.9	42.7	9.27
	IGCC	1.96	271	40.4	50.5	30.4
BICE	ST	3.17	439	79.3	73.9	41.3
	IGCC	2.95	408	61.2	79.7	49.4
BrC	ST	3.18	441	46.4	57.3	24.6
	IGCC	1.81	251	32.3	54.9	36.3
NG	ST	1.87	258	45.6	41.3	22.2
	OCGT	1.54	213	50.4	35.9	20.1
	CCGT	1.31	181	34.7	45.8	32.4
LNG	ST	3.74	518	76.1	59.9	21.5
	OCGT	3.99	553	84.2	56.0	14.9
	CCGT	2.70	374	61.6	64.0	36.2

Each of the fossil fuel and technology combinations for electricity generation from Australian fossil fuels contains four subsystems. Figure 5.3.1 shows the contribution of each subsystem to the total economic indicator magnitude for each combination. The generation subsystems of OCGT systems (H and K) have negative VA, as the sales price is insufficient to repay fuel costs and operating expenses. However, OCGT systems generally operate only when the sales price of electricity is high. The distribution of subsystem contributions for the economic indicators is more even than the environmental indicators (see Figure 5.2.1). Environmental indicators tend to have dominant contributions from either the generation or mining subsystem. The contribution of the transport subsystem to LNG system's I and AC indicators includes liquefaction, ocean transport, vaporisation and pipeline transport.

The VA indicator shows both BrC systems generate greater wealth than do any of the

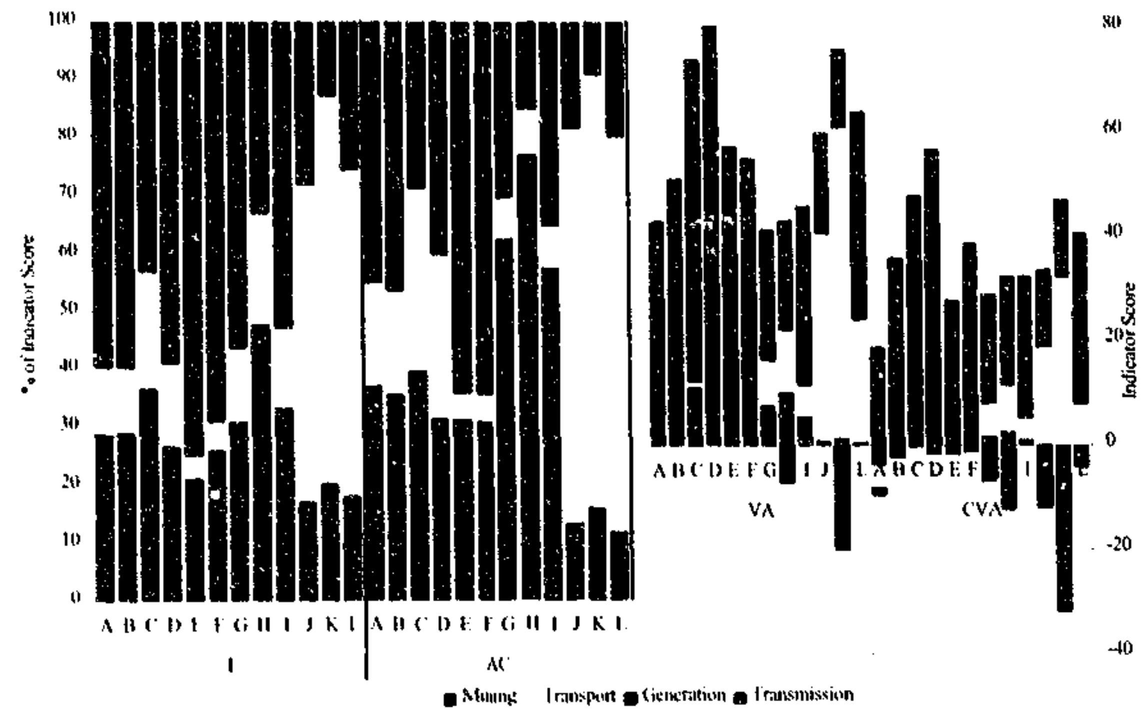

Figure 5.3.1: Subsystem contributions to the economic indicators for electricity generation from Australian fossil fuels (A-L as in Figure 5.2.1). Subsystem contributions for I and I_R are identical. Tabulated subsystem contributions appear in Section A3.2 (Appendix 1).

BIC and NG systems. The AC indicator shows that the ST-BIC system produces least wealth. Furthermore, the AC indicator shows that the CCGT-NG system produces the greatest wealth of the systems currently available, but the IGCC-BrC system offers the potential for even greater wealth generation. The I indicator shows that, of the domestic alternatives, the NG systems have the lowest capital costs, while the ST-BrC systems have the greatest capital costs. Unexpectedly, the IGCC-BrC system has the lowest capital costs of any coal (BrC or BIC) system.

When considering the export systems, the best LNG systems (CCGT-LNG) have lower I, than the best BICE systems (IGCC-BICE). The VA and CVA indicators show IGCC-BICE generating significantly greater wealth than the CCGT-LNG systems. Yet, the AC indicator scores are virtually identical. As the sales of electricity are identical for each system (1 MWh), this indicates that these two systems have equivalent wealth generation.

5.3.3 Sensitivity Analysis

The sensitivity analysis tests the influence of three decisions on the indicator values:

transport distances (for LNG and BICE systems); electricity generation efficiency; and the assumed system capacity. The results of the sensitivity analysis have the same form as the main results shown in Table 5.3.1[‡].

The variation of BICE transport subsystem destination from Japan to Europe worsens all the economic indicators by a minor amount (less than 8 %). The variation of LNG transport subsystem destination from Japan to U.S.A. worsens I by a small amount (less than 5 %), VA and AC by a larger amount (less than 20 %), and CVA by a substantial amount (27-90 %). Significantly, the CVA value for OCGT-LNG systems is negligible for transport to the U.S.A. (less than $ 1 per MWh).

Increasing the electrical generation efficiency improves all the economic indicators generally by small amounts (less than 10 %), except for NG- and OCGT-LNG systems where improvements are uniformly greater (26-260 %). The improvements in CVA of ST-BIC and NG- and ST-LNG systems are greater than for other ST systems (18-45 %).

Increasing the assumed system capacity (i.e. size) from 500 to 2000 MW obviously increases (worsens) their capital cost requirements (I) (between 151 % and 226 % of the cost of a 500 MW system). However, per unit of output, I_R ($ per MWhpa), capital requirements improve (20 % to 40 %). Larger plants often have reduced investment and operating expenses per unit of output (economies of scale). AC, VA and CVA generally improve by 6 to 45 %, but the improvements in CVA are greater.

5.3.4 Summary of Economic Indicator Results

The economic indicators presented here can show the influence that investment and operation of electricity generation systems have on the economy. The subsystem indicators establish the proportional influence of each subsystem on the total system indicator. Comparisons of these indicators allow the ranking of each electricity generation system for economic impact. A discussion of the results of the sensitivity analysis will establish the robustness of these rankings to data variability and assumptions. Chapter 6 discusses the implications of these results on the sustainability of each electricity generation system.

[‡] See footnote *, page 174.

5.4 SOCIAL INDICATOR RESULTS

5.4.1 Overview of Social Indicator Results

Social indicators are a third type of indicator of sustainability. These indicators present simple measures of two causes of impacts on social welfare: employment and employee health and safety. Thus, this section presents indicators of social sustainability for each of the electricity generation systems.

Section 5.4.2 presents social indicators for each electricity generation system. As for the environmental indicators (see Section 5.2), Section 5.4.2 also presents estimates of the contribution of each subsystem to the system indicators. Section 5.4.3 presents the results of the sensitivity analysis, which estimates the affect of value-based decisions on the indicators.

5.4.2 System Indicator Scores

Sections 4.3.2 to 4.3.6 (Chapter 4) contain the data required to produce the social indicators. Sections 4.3.2 to 4.3.4 contain this data on a subsystem basis, and Section 4.3.6 contains factors for its conversion to system basis (Chapter 4). No further manipulations are necessary for the social indicators. The social indicators produced using this method appear in Table 5.4.1.

Each of the fossil fuel and technology combinations for electricity generation from Australian fossil fuels contains four subsystems. Figure 5.4.1 shows the contribution of each subsystem to the total social indicator magnitude for each combination.

Table 5.4.1 shows that BIC and BICE systems have the greatest direct (ED) and indirect (EI) employment. In these systems the mining, transport and generation subsystems each require comparatively greater employment than the corresponding stages of other systems. BIC and BICE systems also have the greatest health and safety impacts, as measured using the lost time injuries (LTI) and fatalities indicators (Fatal).

5.4.3 Sensitivity Analysis

The sensitivity analysis tests the influence of four decisions on the indicator values: transport distances (for LNG and BICE systems); electricity generation efficiency; the assumed system capacity; and the chosen multipliers for indirect employment. The

Table 5.4.1: Social indicators for electricity generation from Australian fossil fuels (ED and EI = direct and indirect employment (10^6 x employees), LTI = lost time injuries (10^7 x LTI), and Fatal = fatalities (10^9 x fatalities), all per MWh of electricity delivered).

Fuel	Technology	Indicator			
		ED	EI	LTI	Fatal
BIC	ST	80.2	449	51.8	10.2
	IGCC	57.2	304	30.3	5.81
BICE	ST	133	735	85.4	14.6
	IGCC	87.4	466	49.2	8.43
BrC	ST	37	212	4.01	0.785
	IGCC	28.9	151	3.11	0.785
NG	ST	52.1	348	9.78	3.92
	OCGT	61.7	444	13.2	4.81
	CCGT	42.2	260	6.93	3.18
LNG	ST	48.2	311	9.09	2.87
	OCGT	58.7	394	12.4	3.88
	CCGT	37.7	234	6.34	2.02

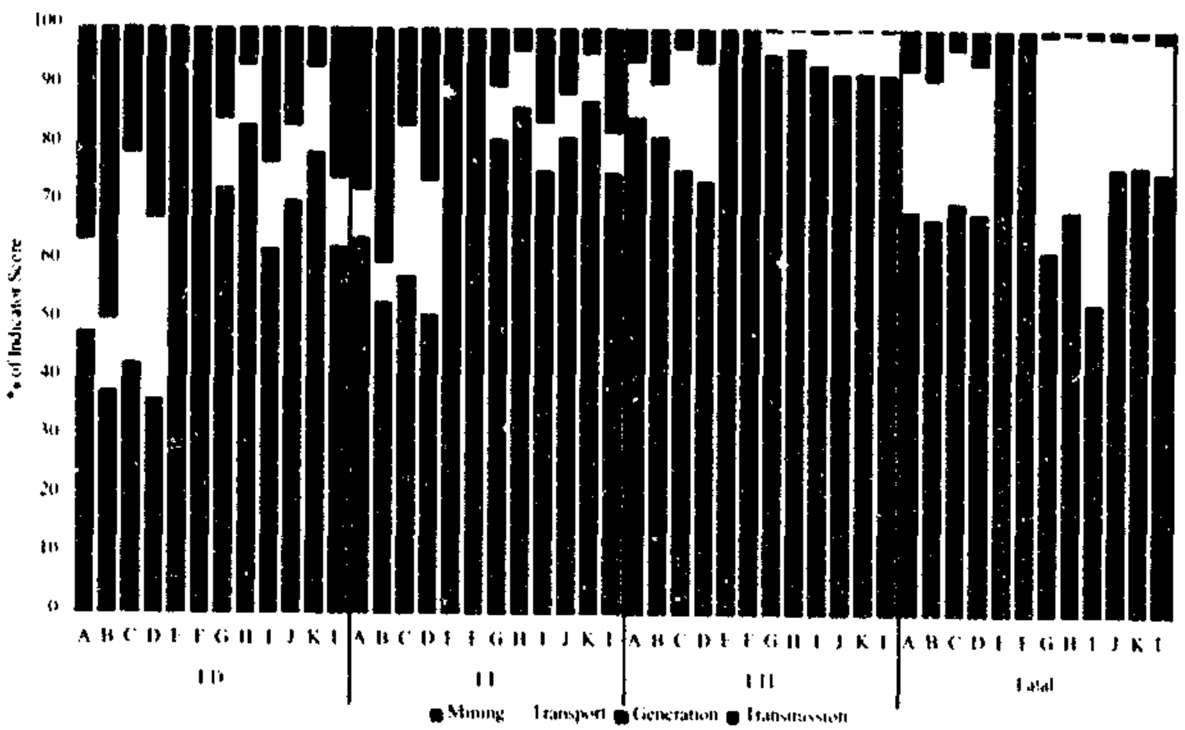

Figure 5.4.1: Subsystem contributions to the social indicators for electricity generation from Australian fossil fuels (A-L as in Figure 5.2.1). Tabulated subsystem contributions appear in Section A3.2 (Appendix 3).

results of the sensitivity analysis have the same form as the main results shown in Table 5.4.1[§].

The variation of BICE transport subsystem destination from Japan to Europe results in no change in any of the indicators. The variation of LNG transport subsystem destination from Japan to U.S.A. increases ED by 12-14 % and EI by 8-9 %, and worsens the LTI and Fatal indicators by approximately 8 % and 23-25 % respectively.

Increasing the electrical generation efficiency decreases EI and ED and improves LTI and Fatal indicator scores. In general, the changes in EI, LTI and Fatal are of the same magnitude as the decreases in ED. Changes are generally between 12 % and 24 %, except for OCGT systems where the changes are nearer 60-80 %.

Increasing the assumed system capacity from 500 to 2000 MW generally decreases EI and ED and improves LTI and Fatal indicator scores by less than 10 %. Improvements in Fatal are greater for ST-BrC and -IGCC (75 %) and ST-NG, -OCGT, and -CCGT (47 % to 57 %) systems.

5.4.4 Summary of Social Indicator Results

The social indicators presented here can show the affect that the operation of electricity generation systems have on the employment and the health and safety of employees. With the toxicity environmental and wealth generation economic indicator, these social indicators allow an understanding of the relative influence of each system on social welfare. Additionally, the subsystem indicators establish the proportional influence of each subsystem on the total system indicator. Comparisons of these indicators allow the ranking of each electricity generation system for social impact. A discussion of the results of the sensitivity analysis will establish the robustness of these rankings to data variability and assumptions. Chapter 6 discusses the implications of these results on the sustainability of each electricity generation system.

5.5 SUSTAINABILITY INDICATOR RESULTS

Production of the final set of sustainability indicators entail the normalisation of the

[§] See footnote *, page 146.

sustainability indicators for each fossil fuel and technology combination. The normalised sustainability indicators indicate the relative importance of their magnitude to that impact within the region. Section 3.5.2 (Chapter 3) contains a discussion of normalisation, and Section 4.3.6 (Chapter 4) presents the normalisation factors for the Australian region. Figure 5.5.1 shows the normalised sustainability indicators produced when dividing the sustainability indicators in Table 5.2.1, Table 5.3.1 and Table 5.4.1 by their corresponding Australian normalisation factors. Each score represents the contribution to Australia's yearly impact on sustainability that the delivery of 1 MWh of electricity to consumers would have, if produced using that system. For example, the ST-BrC normalised CC indicator score represents the contribution that 1 MWh of electricity produced in a ST-BrC system would make to the yearly CC score for Australia. HT, ET, PM and WD are not normalised, due to a lack of comprehensive Australian data for the contributing substances of most importance.

Figure 5.5.1 shows that many of the normalised indicator scores are of similar magnitudes. All of the environmental indicators and the VA economic indicator have magnitudes between 10^{9}-10^{10}. The AC, ED, LTI and Fatal indicators each are one magnitude smaller, or 10^{11}. Only for I** is the magnitude greater, indicating that this indicator has great importance.

Of the normalised environmental indicators, CC has the greatest magnitudes of any emission-related indicator, but the AD and EU indicator scores are of similar magnitudes. The resource depletion scores are of higher magnitude when considering the needs of the world (RD W, EN and EX), than when considering Australia alone (RD A). Thus, Australia is relatively rich in resources necessary for its electricity generation systems. The greatest differences for RD W and RD A are in the domestic coal cases (ST-BrC, ST-BIC, IGCC-BrC, and IGCC-BIC), highlighting the abundance of coal resources available for Australia's future development.

Of the economic indicators of wealth generation, VA and CVA are of greater magnitude than AC.

The magnitudes of the LTI and Fatal social indicators are very similar, indicating that electricity generation systems are equally great contributors to both Australian worker injuries and fatalities.

** The normalised I indicator is the normalised relative capital cost (I_R) (see Table 5.3.1).

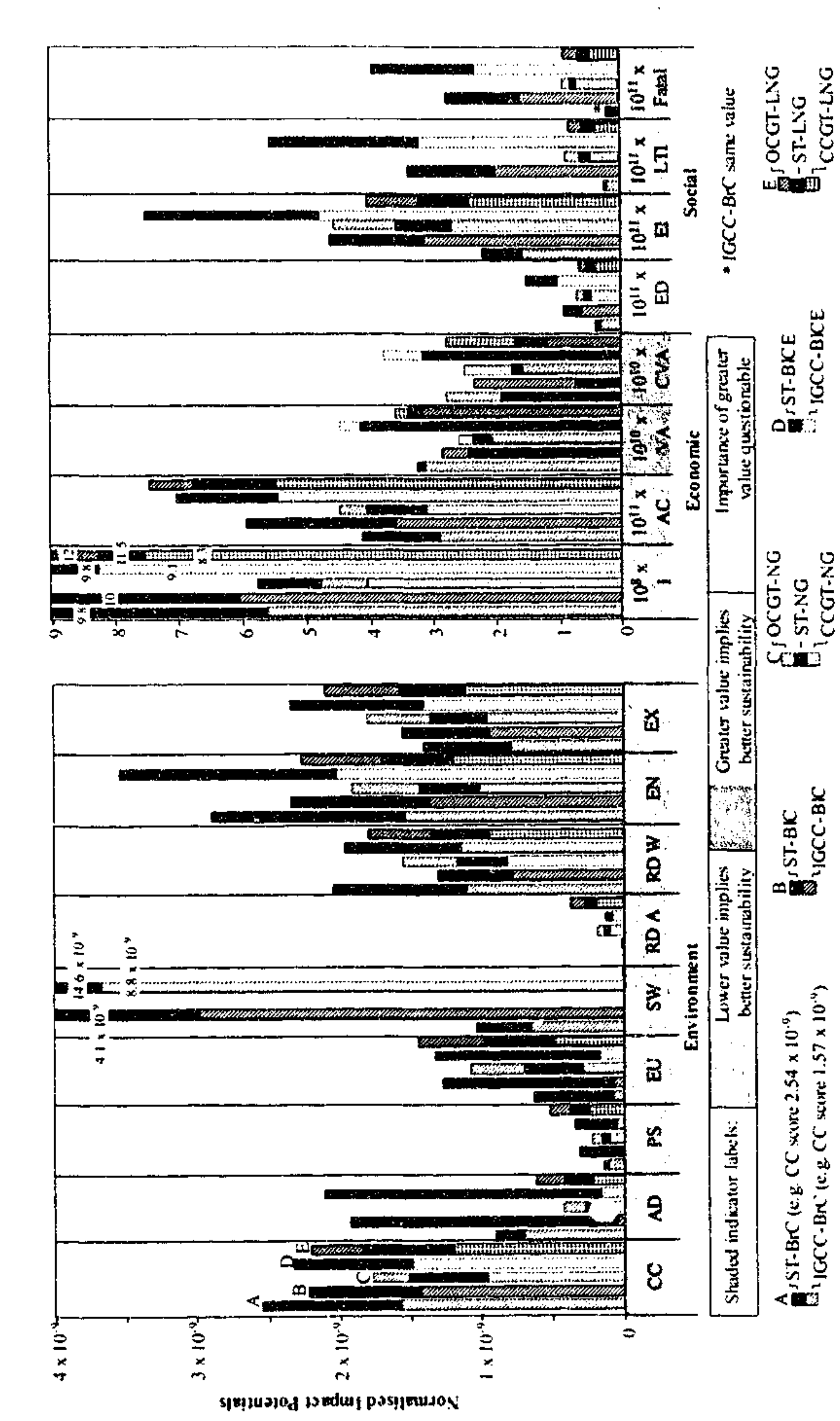

Figure 5.5.1: Sustainability indicators for electricity generation from Australian fossil fuels normalised using Australian data. Numbers at top indicate the magnitudes where scores exceed the scale). Section A3.3, Appendix 3 contains a table of these indicator scores.

5.6 SUMMARY OF RESULTS OF THE SUSTAINABILITY ASSESSMENT

It is possible to generate the sustainability indicators for electricity generation systems. Examination of these indicators enables the identification of which system has the poorest score for each of the impacts on sustainability known to be important to electricity generation systems. CCGT-NG systems have best scores for almost all of the indicators. Importantly, the environmental indicators show that no one system has worst scores for every indicator. Thus, this evidence does not indicate that consuming BrC for electricity generation is necessarily worse for the environment than NG and BlC. The normalisation procedure allows the estimation of the significance of each indicator to Australia's annual contribution of impacts on sustainability. This procedure highlights capital requirements (I) as being most important, while all of the environmental indicators have similar significance.

The non-generation subsystems are substantial contributors to the magnitudes of the system indicators. These contributions are not uniform for all indicators and systems.

The analysis of data uncertainties indicates that the ST-BrC system indicators are less uncertain than the ST-BlC system indicators. However, the uncertainties in bot' f these system's indicators are very large. The analysis of the sensitivity of the indicators to assumptions indicates, that some indicator scores are highly influenced by: LNG allocation procedure (environmental indicators); LNG transport distance (economic); efficiency (all); and assumed system capacity (economic and social indicators). The sensitivity of the indicators of different systems is not uniform. For example, the ST-BrC system's CVA indicator improves by 6.7 % from minimum to maximum electrical efficiency, while for OCGT-NG systems the improvement is 133.8 %.

Therefore, further discussion is necessary to determine the implications of these results on the sustainability of electricity generation systems and to assess the performance of the developed method for sustainability assessment.

6. IMPLICATIONS OF THE SUSTAINABILITY ASSESSMENT

6.1 OVERVIEW OF THE IMPLICATIONS OF THE SUSTAINABILITY ASSESSMENT

The major outcome of Chapter 5 is the production of indicators of sustainability for electricity generation systems, which consume Australian fossil fuels. These indicators are measures of a number of impacts on the economy, the environment and social welfare. What do these measures imply about the relative impacts on sustainability of each electricity generation system? Can one identify the best or worst performing electricity generation system from indicators of individual impacts on sustainability? Section 6.2 seeks to answer these and related questions.

This thesis develops a method for the sustainability assessment of electricity generation systems. Its basis is the use of individual indicators to measure each type of impact on sustainability and it incorporates many tools designed exclusively for environmental assessments. Section 6.3 discusses the merits of the sustainability assessment method.

Section 2.4.2 (Chapter 2) claims that the measurement of sustainability should allow a more comprehensive basis for the planning of electricity generation networks. Section 6.4 discusses the potential of using indicators produced with the developed method as the basis for assessing changes to electricity generation networks. The sustainability assessment method may be useful in assessing the sustainability of systems other than electricity generation systems. Section 6.4 also discusses the potential for the sustainability assessment method to be a generalised tool for assessing impacts on sustainability.

Chapter 7 contains the formal conclusions for this chapter.

6.2 SUSTAINABILITY INDICATORS OF ELECTRICITY GENERATION

6.2.1 OVERVIEW OF SUSTAINABILITY INDICATORS OF ELECTRICITY GENERATION

This section discusses the relative sustainability of the electricity generation systems and discusses the implications of using these indicators.

Section 6.2.2 discusses the relative sustainability performance of the electricity generation systems based on the indicator and normalised indicator scores. Section 6.2.3 discusses the implications of the use of the 'life-cycle' perspective on the indicated sustainability performances. Section 6.2.4 discusses the implications of some limitations highlighted during the uncertainty and sensitivity analysis, and the gathering of data for the electricity systems.

6.2.2 SUSTAINABILITY PERFORMANCE

6.2.2.1 OVERVIEW OF SUSTAINABILITY PERFORMANCE

Section 6.2.2.2 discusses the domestic systems, which consume BIC, BrC and NG, while Section 6.2.2.3 discusses the export systems, which consume BICE and LNG.

6.2.2.2 DOMESTIC SYSTEMS

The electricity generation systems consuming brown coal (BrC) have middle to bad environmental indicators, some good and some bad economic indicators and good social indicators. Of the environmental indicators, climate change (CC), world resource depletion (RD W), and energy depletion (EN) have worst scores. Reducing CC is the goal of most ST-BrC system operators (see for example, Loy Yang Power (2000)). Proposed methods include: pre-drying the coal, using advanced electricity generation technology (i.e. IGCC) and changing to another fossil fuel (fuel switching). Drying the coal may reduce water contents from BrC to 20-25 %, thus increasing the energy density of the fuel and electricity generation efficiency (Strauss *et al.* (2001)), improving CC scores in a ST-BrC and reducing the capital cost of the generation subsystem (see Section 4.3.3.3.1, Chapter 4). However, emerging technologies for

drying coals, such as the MTE, are not yet ready for commercialisation in Australia. There are many proposed advanced electricity generation technologies for BrC, one of which is the assessed IGCC-BrC system. The replacement of existing ST-BrC systems with IGCC-BrC systems results in a 38 % reduction of the CC indicator. Fuel switching for ST-BrC systems is not simple. The design of ST-BrC systems is such that existing generation subsystems cannot replace BrC with BIC or NG without major modifications. The discussion of BrC systems (Section 4.3.3.3.1, Chapter 4) states that the boiler temperatures for BrC are lower than for BIC and NG. Consequently, the tubing within the boiler is unable to survive at the higher temperatures caused when consuming BIC or NG. Thus, changing fuels may require the complete replacement of the boilers, which are expensive items. Potentially, replacing a ST-BrC with:

- a ST-BIC or ST-BICE system reduces CC by 13 % or 9 % respectively;
- IGCC-BIC and IGCC-BICE system reduces CC by 35-40 % (similar to an IGCC-BrC system); and
- a CCGT-NG system reduces CC by 62 %.

Figure 5.5.1 (Chapter 5) enables broader sustainability perspective on the benefits of these options for CC reduction. The IGCC-BrC option betters all indicators except value added (VA) and employment (direct (ED) and indirect (ID)). Furthermore, the I value for IGCC-BrC systems, includes new mining, transport and transmission subsystems. A new IGCC-BrC system may use the existing subsystems, from the replaced ST-BrC system, and thus its I value will be lessened from \$ 1.81 billion to \$ 1.04 billion (AUD 2000) (I from Table 5.3.1 and Figure 5.3.1, Chapter 5). The BIC options significantly worsen acidification (AD), eutrophication (EU), solid waste generation (SW), annualised costs (AC), VA, lost time injuries (LTI) and fatalities (Fatal) and improve RD W, EN, ED, EI and capital requirements (I). The CCGT-NG option significantly worsens Australian resource depletion (RW A) and VA, but improves all other categories.

The resource depletion indicators (RD A, RD W, EN and exergy destruction (EX)) show BrC systems as both worst and best, depending on the indicator. The RD W indicator shows the ST-BrC system as worst, while the similar RD A indicator, shows it to be better than all systems except the more advanced IGCC-BrC. The two indicator normalised scores have different magnitudes (RD W 10^9, RD A 10^{11}), indicating different relevancies to Australia. BrC consumption is the major contributor to both indicators scores. This indicates that the consumption of BrC in Australia has less relevance to the sustainability of Australia than the world*. The EN indicator shows ST-BrC as the worst system, while the similar EX indicator shows ST-BrC as a mid-range system. This indicates that the processes used to generate electricity from BrC consume relatively large amounts of energy resources, but are relatively more efficient at extracting useful energy (exergy) from those resources.

Of the economic and social indicators, I is worse and ED and EI are lower for BrC systems than for other fuels. The IGCC-BrC I indicator score, which includes coal drying, is much lower than the ST-BrC score, and similar to the I indicators of IGCC-BlC systems. However, the reliability of this estimate is unknown, as the used IGCC and MTE dryer technologies are in their infancy (see Section 4.3.3.3.1, Chapter 4). The integrated nature of the BrC generation system, with one company generally owning the mining, transport and generation subsystems, aids in limiting costs (as shown by AC). Consequently, fewer employees are necessary. For example, only one senior management team is necessary, rather than three. In addition, similar tasks in the subsystems, such as maintenance, may require only a single maintenance team.

The electricity generation systems consuming black coal (BlC) have middle to bad environmental indicators, middle to bad economic indicators and good and bad social indicators. Of the environmental indicators, CC, AD, EU and SW have worst scores. As with BrC, the goal of most companies operating BlC electricity generation systems is the reduction of CC. The replacement of existing ST systems with IGCC systems, would improve CC (by 36 %), SW (by 28 %) and EU (by ~100 %). This also results in improvements in all economic and social indicators. Changing fuel to NG significantly improves the CC indicator, and the AD, PS, EU and SW indicators. Unlike BrC, it is possible to consume NG fuel in existing ST-BlC plants, with minimal capital expenditure. This change (to ST-NG) would improve the CC indicator by 32 % over ST-BlC systems.

Improving AD requires reducing emissions of NO_x and SO_2. Of these emissions, the control of SO_2 is more common as SO_2 has a greater relative contribution to AD. The introduction of equipment to reduce SO_2 emissions ('desulfurisation') to power stations in each case would substantially improve the AD (by up to 96 %). These systems

* This view is simplistic (see Section 6.3.3).

commonly consume limestone, producing gypsum. Gypsum is a useful material; extensively used in the manufacture of plasterboard, as a soil conditioner, and elsewhere. However, the lack of the use of desulfurisation indicates that it is not economic to produce gypsum in Australia in this manner. Thus, the likely destination of the generated gypsum would thus be landfill, further increasing the already large solid waste indicators of these systems. Moreover, the desulfurisation process will consume energy, for example in the preparation and pumping of the limestone-water slurry. Therefore, the addition of desulfurisation improves AD, but correspondingly worsens SW and other emission related indicators (i.e. CC, EU and PS). Such a modification will worsen I (for the desulfurisation equipment), AC, VA and CVA (all due to limestone purchase and gypsum disposal costs). It may also improve ED and EI, while worsening LTI and Fatal (through increased transport and bulk material handling activity). The use of desulfurisation in Australia is unlikely as BlC industry sources claim: 'SO_x emissions are not an issue in Australia due to a combination of low sulfur coals and low industrial intensity. There is also generally a higher tolerance of Australian flora to SO_x' (BHP Minerals Technology (2001))†. Therefore, the addition of desulfurisation without regulations enforcing reductions in SO_2 is unlikely.

The resource depletion indicators (RD A, RD W, EN and EX) show BlC systems as middle range performers. The RD W, RD A, EN and EX indicators show the ST-BlC system as between the performances of the ST-BrC and CCGT-NG systems. As with BrC, the RD W and RD A indicator normalised scores have different magnitudes (10^9 and 10^{11}), indicating different relevancies to the world and Australia. BlC is the major contributor to RD W, while other fuels (i.e. diesel) contribute significantly to RD A. This indicates that the consumption of BlC in Australia has lesser relevance, than the consumption of other fuels, to the sustainability of Australia than the world.

Of the economic and social indicators, AC, CVA, LTI and Fatal are worse, while ED and EI are better for BlC systems than other fuels. While BlC systems have lower I than ST-BrC systems, the costs of mining and transport of BlC (fuel costs) are significantly higher. The product of the AC indicator scores for ST-BrC and ST-BlC from Table 5.3.1 (Chapter 5) and the fractional contributions of the mining and transport subsystems from Figure 5.3.1 (Chapter 5) provides an estimate of the costs of fuel for the two systems: \$ 16.6 (AUD 2000) per MWh for ST-BrC and \$ 36.7 (AUD

† In this thesis, SO_2 and SO_x are interchangeable.

2000) per MWh. Thus, even though the ST-BrC system consumes approximately 3 times as much coal (see Tables 4.4.20 and 4.4.9, Chapter 4), its fuel costs are less than the ST-BIC system. While relativities between prices paid for fuels are not necessarily similar to the relativities between their costs of production, examination of the relative prices paid for BIC and BrC at the generation subsystem (see Table 4.3.52, Chapter 4, column 'Transport'), indicates higher underlying costs for BIC fuel production. Comparatively poor CVA scores also indicate higher fuel costs for BIC (CVA excludes labour costs).

BIC systems have greatest employment, measured using ED and EI. The mining, transport and generation subsystems each have comparatively greater employment than the corresponding subsystems for the other fuels (see Figure 5.4.1, Chapter 5). However, BIC systems also have the greatest health and safety impacts, as measured by LTI and Fatal. The greater number of employees (ED) for BIC systems could conceivably cause the high LTI and Fatal scores, as these safety incidents are associated with workers. This supposition will be true if the ratios of LTI and Fatal to ED are similar for each system (see Table 6.2.1). Table 6.2.1 shows that the LTI/ED and Fatal/ED ratios for the BIC systems are much greater than for the other systems. Mining, particularly underground, is the greatest contributor to the safety indicator scores of BIC systems (see Figure 5.4.1, Chapter 5). In BIC mining, approximately four fatalities occur per annum (National Occupational Health & Safety Commission (2002)). For NG and LNG mining less than one fatality occurs per annum (National Occupational Health & Safety Commission (2002)), while since 1993 there have been no BrC mining fatalities (Natural Resources and Environment (2001)).

As with BrC, the use of the advanced technology IGCC-BIC systems, rather than ST-BIC systems, enhances all economic and social indicators (except for ED and EI). The IGCC-BIC systems consume less coal, and thus require smaller coal mining and transport subsystems.

The electricity generation systems consuming natural gas (NG) have good to bad environmental indicators, good to bad economic indicators and middle social indicators. Of the environmental indicators, PS and EU have poor scores. NG systems emit proportionally greater quantities of NO_x than the other fuels. Emissions of NO_x heavily influence the PS and EU indicators. However, the CCGT-NG systems have much lower impacts than the OCGT-NG and ST-NG systems. Consequently, the replacement of

Table 6.2.1: Ratios of LTI to ED and Fatal to ED, to indicate the frequency of safety incidents per employees for Australian electricity generation systems (LTI, Fatal and ED from Table 5.4.1, Chapter 5).

Fuel	Technology	Ratio	
		LTI/ED	Fatal/ED
BIC	ST	0.646	0.127
	IGCC	0.530	0.102
BICE	ST	0.640	0.110
	IGCC	0.563	0.097
BrC	ST	0.108	0.021
	IGCC	0.108	0.027
NG	ST	0.188	0.075
	OCGT	0.213	0.078
	CCGT	0.164	0.075
LNG	ST	0.188	0.059
	OCGT	0.211	0.066
	CCGT	0.168	0.054

current ST and OCGT systems with CCGT systems should be a priority, especially in locations where such plants are in operation over extended periods. Operation of OCGT systems for utility generation has hitherto been for peak power provision, but the use of OCGT systems for private electricity generation is common in Australia.

The resource depletion indicators (RD A, RD W, EN and EX) show NG systems as good and bad performers depending on the employed generation technology. The RD W indicator score for CCGT-NG systems is near best, while the OCGT-NG system's score is worse than ST-BIC systems. However, the RD A indicator scores for NG systems are much greater than the other fuels. Thus, the consumption of NG in Australia has greater resource depletion relevance to Australia than the consumption of BrC or BIC. As with BrC, the RD W and RD A indicator normalised scores have different magnitudes (10^9 and 10^{11}), indicating different relevancies to Australia and the world. NG is the major contributor to RD W and RD A, indicating that the consumption of NG has lesser relevance to the sustainability of Australia than the world.

Of the economic and social indicators, VA indicators are poorer, while I, CVA and EI are better for NG systems than for other systems. NG systems require less capital (I) than other systems, as their generation subsystems are less complex than the corresponding BlC and BrC systems (requiring no fuel storage, fuel treatment or flue gas cleaning) and produce little ash. A further consequence of this reduced complexity and capital investment is reduced construction time. This in turn, reduces the interest accrued during construction and the risk of large time and expenditure overruns. The poor VA scores may indicate higher production costs for NG systems than for the other fuels, as electricity price is a constant. Yet, the AC indicator shows that production costs of NG systems are not highest. This is due to the definition of VA, which states that VA depends on two other factors: sales (S) and labour costs (L) (Equation 3.3.3, Chapter 3). A high L will worsen the VA indicator scores. The ED indicator shows NG systems to have higher employment than BrC systems and lower employment than BlC systems. In contrast, NG systems have good CVA scores due to their low I scores.

Of the domestic systems, consuming BrC, BlC and NG, CCGT-NG systems have best scores for most indicators. Nevertheless, their RD A scores are worse than for the other fuels, indicating greater scarcity within Australia for the combustion of NG over BrC and BlC. Both IGCC-BrC and IGCC-BlC systems have better RD A indicators, but their other indicators are generally much worse than CCGT-NG systems. Of the two IGCC systems, BrC systems have generally better indicator scores, especially economic and safety indicators. Yet, the IGCC-BrC system has a greater CC indicator. IGCC-BrC and IGCC-BlC systems are not yet commercially available (see Sections 4.4.2.3.1.1 and 4.4.3.3.1.1, Chapter 4). These results highlight the importance of accelerating the development of these IGCC systems, and the MTE dewatering technology that allows the IGCC-BrC to function, to fulfil their promised high performance and low cost.

6.2.2.3 *Export Systems*

The electricity generation systems consuming export fuels, black coal (BlCE) and liquefied natural gas (LNG) systems, have worse environmental indicators than their equivalent domestic (BlC and NG) systems. For the BlCE systems the changes are generally minor except for the SW indicator, derived from the need to clean the coal. The coal cleaning process rejects a large amount of the coal mined in the mining stage (up to 30 % of raw coal is lost as solid waste). BlCE systems also emit more particulates than BlC systems, as in the transport system a greater number of stockpiling and handling operations occur. In the BlCE systems, coal stockpiling may occur at the

mine, domestic port, foreign port and power station. In contrast, in the BlC systems, coal stockpiling occurs only twice, at the mine and power station. For the LNG systems, the changes are considerable, due to substantially greater: fuel gas consumption in the liquefaction of NG to LNG; LNG and fuel oil consumption during transport, and NG consumption during subsequent vaporisation of LNG. The scores of the OCGT-LNG system are substantially worse than all other natural gas and LNG systems, due to the low electricity generation efficiency of these systems.

The resource depletion indicators (RD A, RD W, EN and EX) show similar trends to those of the other environmental indicators. Yet, the RD A score for BlCE systems worsens, from the performance of BlC systems, out of proportion to the other indicators. This is due to the consumption of fuel oil in the ocean transport part of the transport subsystem. The reserves necessary to produce fuel oil (i.e. crude oil) in Australia are much smaller than NG, BlC and BrC reserves. Thus, the consumption of fuel oil in Australia has a much higher relevance to sustainability (as characterised by their equivalence factors, CF) than the consumption of NG, BlC or BrC. The same does not occur for RD W, indicating that fuel oil has lesser relevance to sustainability for the world than for Australia.

Of the economic indicators, I and AC worsen, but the higher prices paid for BlCE, LNG and electricity in the export destination country (Japan, see Table 4.3.52, Chapter 4) ensure they have better VA and CVA scores. Of the social indicators, the BlCE systems have better employment (ED and EI) scores and worse safety (LTI and Fatal) scores than the corresponding BlC systems. The cause of these effects is the necessity of mining greater quantities of coal in the mining subsystem, to allow for coal cleaning. Meanwhile, the LNG systems have slightly better social indicators, than NG systems, due to the lower direct employment (ED) necessary for LNG systems.

Of the export systems, consuming BlCE or LNG, LNG systems have better scores than ST-BlCE systems (except for OCGT-LNG systems). Switching to IGCC-BlCE systems would enable better indicator scores than the ST-LNG and OCGT-LNG systems, except for the SW and safety (LTI and Fatal) indicators. However, greater benefit results from switching to CCGT-LNG systems, which have best scores for all indicators except for RD A and the employment indicators (ED and EI). As earlier shown when discussing domestic NG systems, the consumption of NG in Australia has greater relevance to Australia than the consumption of BlC. Consequently, the RD A indicator for CCGT-LNG systems is worse than both the IGCC-BICE and ST-BICE systems.

6.2.2.4 OVERALL

The indicators of sustainability in Chapter 5 indicated no one system has either best or worst environmental indicator scores for every indicator. Comparing the relative contributions to each sustainability indicator shows the relative performance of systems for each indicator (see Sections 6.2.2.2 and 6.2. 3). The use of the normalisation method establishes that most impacts are of similar importance to Australia's yearly impacts on sustainability (see Section 5.5, Chapter 5). The importance of the capital expenditure indicator (I) to Australia appears greater than are any of the other indicators. Thus, electricity generation projects are highly significant investments of capital. The normalised SW indicators of BIC and BICE systems also have similar magnitudes to the normalised I indicator. However, the source of the normalisation value for SW (see Table 4.3.49, Chapter 4) does not detail all inclusions. Thus, it may exclude solid wastes from electricity generation and other similar industries and understate Australian annual solid waste generation. As this normalisation factor is uncertain, the magnitude of the normalised SW indicator is also uncertain. The basis for most recent comparisons of electricity generation has been economic indicators, such as AC, and CC (see Section 1.1, Chapter 1 and Section 2.4, Chapter 2). As the normalised indicators of other impacts have similar magnitudes, the basis for these comparisons should be broader, including all of these indicators.

6.2.3 'LIFE-CYCLE' PERSPECTIVE

Sustainability assessment requires the use of the 'life-cycle' perspective (see Section 2.3.5, Chapter 2). A glance at the subsystem contributions figures of Chapter 5 (Figures 5.2.1, 5.3.1 and 5.4.1) shows that substantial proportions of each of the indicator scores are from subsystems other than the generation subsystem. Some indicators would lose all relevance if measured with a boundary restricted to the generation subsystem alone. For example, the social indicators, LTI and Fatal, have minimal contributions from the generation subsystem. Without the mining subsystem contributions, these indicators for all systems are very similar. Thus, the knowledge that BIC and BICE systems have

considerably greater LTI and Fatal indicator scores would have been lost. Additional examples with important contributions from non-generation subsystems include: for LNG systems, energy consumption in mining due to the liquefaction of NG and for BICE systems, solid waste generation in mining due to coal cleaning.

Contributions to impacts on sustainability may be large in real terms even when they have small indicator scores, if the output of the system (i.e. electricity) is large, as is typical for these systems. The product of the indicator score (i.e. kg per MWh) and the output (i.e. MWh per annum) represent the real impact on sustainability (i.e. kg per annum).

Subsystem contributions may indicate where the best opportunities are for improving performance. For example, trying to improve the health and safety (LTI and Fatal) performance of a BiC or BICE system by improving performance in the generation subsystem will have little effect (see Figure 5.4.1, Chapter 5). The most effective way to improve system health and safety performance is by improving health and safety performance in the mining subsystem. Accordingly, an assessment of the impacts of sustainability caused by electricity generation systems, determined with these subsystems absent, would be misleading.

The system boundary used is not strictly speaking compatible with the 'life-cycle' perspective. Section 4.2.3 (Chapter 4) highlights exclusions from the analysis, such as construction, decommissioning and secondary processes. The ability to exclude parts of the 'life-cycle' is necessary to ensure both the data collection and sustainability assessment remain manageable (Section 3.2.3.3, Chapter 3).

6.2.4 LIMITATIONS

6.2.4.1 UNCERTAINTY ANALYSIS

Uncertainty analysis is necessary to establish the robustness of the sustainability indicators to uncertainty in data used in their calculation (see Section 3.5, Chapter 3). Yet, there are no established methods for uncertainty analysis of assessments using 'life cycle' boundaries (see Section 3.2.3.7, Chapter 3). Therefore, this assessment investigates some uncertainty appraisal methods for the CC, AD and RD W environmental indicators of the ST-BrC and ST-BIC systems. The results of this investigation are in Section 5.2.3 (Chapter 5).

The first method is a numerical Monte-Carlo analysis (see Section 3.2.3.7.2, Chapter 3). The results indicate that there is large uncertainty in the indicators, as characterised by the standard deviation (SD) (see Table 5.2.2, Chapter 5). Thus, it is possible to obtain a wide range of scores for the three indicators. Moreover, these ranges overlap. Therefore, while the indicators in the first line of the table, calculated using average values of input data, show worse CC and RD W indicators for ST-BrC systems, but a better AD indicator, it is possible for these conditions to reverse. For example, if a ST-BlC system has low electricity generation efficiency, its CC and RD W scores can be worse than for a ST-BrC system having high efficiency. The normalised difference method (see Figure 5.2.2, Chapter 5) shows, in an objective manner, that there is a greater probability that ST-BlC systems have better CC scores than ST-BrC systems. In all likelihood, the use of this method on other indicators will show that the probability that the relative performances of the systems shown in Chapter 5, is high for most, if not all, indicators. In these other cases, the probabilities are likely to be similar (for example, there may be 45 % probability that a ST-BrC is better than a ST-BlC, and a 45 % probability that the ST-BlC is better than the ST-BrC for the same indicator). Thus, this type of uncertainty analysis is useful in proving that the identified differences between the systems are real and likely to occur in practice.

A separate Monte-Carlo analysis of contributions to the uncertainty in the CC indicators establishes that electricity generation efficiency is the largest contributor for both systems (see Table 5.2.3, Chapter 5). Thus, the variation of efficiency provides a fair approximation of the quantitative uncertainty of the systems. The removal of uncertainty due to this efficiency established that the scale of uncertainties due to other data sources for both systems is similar. Thus, the difference in the scale of uncertainty for both systems (BlC 309, BrC 102) is due mainly to the efficiency data.

The greater uncertainty in the BlC efficiency data is due to the wide range of efficiencies in Australian ST-BlC systems. Electricity generation efficiency varies with both plant age and design. Even the efficiency of an individual power station may also fluctuate during operation, with changes in operating conditions. Some important influences on efficiency during operation include variances in fuel quality, ash deposition on boiler tubes, startup and shutdown, and electricity generation at design, high or low levels. For the ST-BrC, the CO_2 emission factor for BrC combustion also is a significant contributor. The moisture content of the coal is the major influence on the

CO_2 emission factor. Three mines produce BrC and the moisture content of BrC in one mine is under 60 %, while in another it can be up to 66 % (by mass) (see Figure 4.3.4, Chapter 4). Such variations in moisture content affect the amount of coal consumed, and thus the consumption and emission of carbon for the same output of electricity.

The qualitative method of Wrisberg (see Table 5.2.4, Chapter 5) shows that reliability and completeness are the major contributors to qualitative error for both systems. The cause of the poor reliability scores is the use of some data without an identified source plant (unverified data) and data based on assumptions. The cause of the poor completeness scores is the lack of data for some facilities within Australia.

The qualitative method of Rousseaux *et al.* (see Table 5.2.5, Chapter 5) shows that the data quality of the ST-BrC systems is better than for the ST-BlC systems. The ST-BrC system uses mainly data obtained directly from the small number of existing systems, of high reliability. Contrariwise, the ST-BlC system uses mainly reports published by a minority of the many existing systems. Thus, the reliability and completeness scores of the ST-BrC system data are better. Both systems have high variability scores for the temporal indicator indicating a wide spread of data temporal scores. Most of the data sources for these systems are recent (within three years of the year of study) having data indicator scores of 1 or 2 (see Table 3.2.3, Chapter 3). However, it also includes a number of very detailed older sources (10 years from the year of study) with data indicator scores of 5. Similarly, the variability score of the ST-BrC system is high as its data includes a small number of estimates (indicator score 5), while most data are plant measurements (indicator score 1). Thus, this method shows more promise in locating and identifying the cause of deficiencies in data quality than does the method of Wrisberg.

The uncertainty assessment does not include the NG systems. Yet, estimation of the likely outcome is possible, using the knowledge collected from the ST-BrC and ST-BlC assessments. Variation of electrical generation efficiency allows the estimation of numerical uncertainty for NG systems. This variation is part of the sensitivity analysis (see Section 6.2.4.2). Qualitative uncertainty is dependent on the qualities of the data sources. The NG systems have a greater reliance on aggregated sector-wide data, due to a lack of public, site-specific, information sources. This evidence suggests that the qualitative uncertainty of the NG systems could be greater than for both the BrC and BlC systems.

6.2.4.2 SENSITIVITY ANALYSIS

Sensitivity analysis is necessary to establish the robustness of the sustainability indicators to decisions and assumptions in their derivation (see Section 3.5, Chapter 3). Therefore, sensitivity analyses have investigated the influence of key decisions and assumptions in the preparation of indicators for each electricity generation system (see Sections 5.2.4, 5.3.3 and 5.4.3, Chapter 5).

Of the environmental indicator sensitivity results, the allocation method and transport distance for LNG systems are the important influences. Using the economic allocation method considerably improves the indicators of LNG systems. However, the economic allocation method predicts a much lower consumption rate of natural gas in the LNG mining subsystem than observed in practice. Thus, the indicators determined using this method are not as representative as those produced using the allocation method based on gas consumption rate. The indicator most affected by varying LNG transport distance is RD A. LNG systems consume NG during transport of full LNG vessels and fuel oil during transport of empty LNG vessels (return journeys after delivery). Section 6.2.2 states that the consumption of NG and fuel oil have greater relative impact on sustainability for Australia than does the consumption of BIC. Of NG and fuel oil, fuel oil has greater relevance to sustainability for Australia. Thus, the RD A indicator is particularly susceptible to transport distance. However, changes to the other indicators are minimal and the magnitude of the normalised RD A indicator is low. Consequently, the robustness of the sustainability performances derived from the environmental indicators in Chapter 5 is high.

Of the economic indicator sensitivity results, the transport distance for LNG systems and assumed system capacity are the important influences. The indicator most affected by varying LNG transport distance is CVA. CVA is the difference between VA and annualised capital (C_R) (see Equation 3.3.14, Chapter 3). When extending LNG transport distance, VA worsens because the operating costs of transport increase. Moreover, it takes greater time to deliver each load of LNG by a transport vessel, requiring more vessels to deliver LNG at the same rate. Thus, greater I is necessary. Both of these changes worsen CVA. The assumed system capacity has important effects on all economic indicators. Each economic indicator includes an estimate of operating or capital cost in its method. All of the operating and capital cost estimations

are power law correlations (see Section 3.3.3.3 and 3.3.3.4, Chapter 3) based on either production capacity (Q) or production (P)[‡]. Thus, assumed system capacity should be a dominant influence on the robustness of the economic indicators. However, an analysis of relative economic performance with very large changes in assumed system capacity shows little variation, except in VA and CVA (see Table 6.2.2). The variations in VA and CVA occur because the increase in electricity sales with capacity (and production) is linear, while increases in costs have power law dependence on capacity. As the indicators show only minor sensitivity to wide changes in these important variables, the robustness of the sustainability performances derived from the economic indicators in Chapter 5 is high.

Table 6.2.2: Changes in the rankings (1 = best, 12 = worst) of different electricity generation systems, using the economic indicators, when the sensitivity analysis changes the assumed system capacity from 500 MW to 2000 MW (1 = ranking improves one place, 0 = no change in ranking, -2 = ranking worsens by two places).

Fuel	Technology	Indicator			
		I	AC	VA	CVA
BIC	ST	0	0	2	-1
	IGCC	1	1	-2	0
BICE	ST	1	0	0	2
	IGCC	0	-1	0	0
BrC	ST	-1	0	-3	1
	IGCC	1	2	-2	-1
NG	ST	-2	-1	-2	-4
	OCGT	0	-2	0	-3
	CCGT	0	0	-2	-4
LNG	ST	0	0	3	3
	OCGT	0	0	5	3
	CCGT	0	1	1	4

Of the social indicator sensitivity results, the transport distance for LNG systems and assumed system capacity have important influences on the Fatal indicator. However, there is a substantial difference between the poor performance of BIC systems, and the better performing NG and BrC systems. Therefore, the relatively small changes to the Fatal indicator, resulting from varying the transport distance, make little difference to

‡ Production capacity directly influences production rates.

their relative social performances.

The final sensitivity analysis varies the electrical generation efficiency of the generation subsystem. Section 6.2.4.1 shows that for these systems, varying electrical generation efficiency provides a rough estimate of the uncertainty of the indicators because of numerical uncertainties in the data used to generate them. For all the systems, the resultant indicator variations are generally between 90 and 110 % of the indicator score for the average efficiency, except for OCGT systems. As with uncertainty assessment, the ranges of many indicators overlap. Section 6.2.4.1 discusses overlap between the CC indicators of ST-BlC and ST-BrC systems. The sensitivity analysis shows that similar overlap occurs for the IGCC-BrC and IGCC-BlC systems. These systems are currently in development, indicating that it may be possible to develop an optimised IGCC-BrC system with CC indicators similar to those of an IGCC-BlC system.

The performance of OCGT systems with low efficiencies (< 25 %) is concerning, given the widespread use of such turbines in industry. The impacts of the lowest efficiency OCGT gas systems are worse than the least efficient coal systems. Hence, from an environmental viewpoint the replacement of low efficiency OCGT gas systems should be a priority, where these operate over extended periods. A particular matter of concern is the current trend of recycling old, inefficient turbines for use in OCGT systems for peak power generation, justified by their projected occasional use. The inefficiencies of the turbines themselves compounded with the inherent inefficiencies of the OCGT technology result in very poor environmental performance. Once installed, unforeseen failures of normally operating, higher efficiency plant may lead to more frequent use of the OCGT system than originally envisioned, with serious environmental penalty.

6.2.4.3 Additional Impacts

The sustainability assessment aims to include impacts of most importance to electricity generation systems (see Section 1.1, Chapter 1). Selection of these impacts has been by critical examination of previous environmental, economic and social assessments of electricity generation (see Section 2.5, Chapter 2). Nevertheless, electricity generation systems contribute to a number of other impacts. Some environmental impacts excluded because of a lack of established or quantitative data include:

- Electromagnetic field (EMF) radiation effects;
- Dioxins in foods;
- Acid mine drainage; and
- Subsidence.

EMF radiation effects on humans, plant and animals are not well understood. Nevertheless, some attribute increases in the incidence of leukaemia (cancers of the blood) in young children to EMF radiation from transmission cables (WHO (2001)). Dioxins are a persistent chemical that has a number of effects on human health, including cancer (WHO (1999)). Many types of industrial processes emit dioxins and electricity generation systems are not the most important emitters. Dioxins concentrate in fatty foods, such as butter, and recent tests have shown that Australian butters have low dioxin concentrations (Kalantzi, *et al.* (2001)). This indicates that dioxin emissions from Australian electricity generation are of comparatively low importance (perhaps due to a lower concentration of emitters). Acid mine drainage occurs when water dissolves some components in coal, increasing its own acidity and toxicity. Acid mine drainage has particularly been a problem for BlC systems, due to the great amounts of overburden and coal moved and stored during mining. Such problems can be minimised through proper management of water flows at mines. Subsidence is the lowering of surface levels through either underground mining or artesian water removal. Underground mining can lead to rapid subsidence and the loss of property and lives. Artesian water removal leads to slow subsidence, over a wide area. Subsidence is a substantial problem for BrC systems (for example, Gloe (1984)).

The economic indicators exclude the risk of failure. Risk is important in economic assessments, as projects with high risk (of failure) are unlikely to proceed to construction. Important contributors to economic risk are: the magnitude of I; the time for construction; sensitivity to capital overruns (i.e. new technologies and first of a kind plant have high sensitivity); and the flexibility to adapt to changes in regulatory or product requirements and to produce wealth if major function fails. NG systems have lower I and construction times than do any of the BrC and BlC systems. Lower I and construction times reduce the risk of cost rises during construction. Sanction estimates of I for new projects characteristically have an accuracy of ± 10 %, so overruns of up to 10 % are not uncommon. An increase of 10 % in I for NG systems is an increase of $

130 to 190 million, while for a ST-BrC system it is $ 320 million. The IGCC-BrC and IGCC-BIC systems are both new technologies. Actual I for new technology systems is often greater than predicted, and thus have higher risk. Another aspect of risk is flexibility. As NG is a widely used fuel and chemical feedstock, the NG production and delivery parts of the NG systems may still generate wealth should electricity generation itself become unprofitable. Thus, NG systems have greater flexibility than do BIC and BrC systems. Furthermore, low I may enable greater flexibility to invest in plant improvements as new technology develops, or in additional plants or other sectors. Investing in additional plants or other sectors spreads risk between the investments (thus, reducing the risk of the entire investment failing to generate wealth), and may enhance wealth generation from the same amount of I. Quantification of this risk is known as risk analysis (Hertz (1964)), and Van Groenendaala and Kleijnen (1997) discuss some methods for risk analysis for large investment projects, including electricity generation and NG transmission subsystems. The measurement of economic risk is beyond the scope of the sustainability method applied in this thesis.

Section 3.4.3 (Chapter 3) identifies that the LTI and Fatal indicators ignore health effects on workers and the nearby public that occur later in life, are long term or 'chronic'. One important effect is the so-called black lung disease, which affects workers exposed to BIC dust (see Page *et al.* (1997)). As the LTI and Fatal indicators of BIC systems are already worse than the other systems, the exclusion of this impact from the indicators would augment this effect. BrC dust shows no such effects on health (Finocchiaro *et al.* (1997)).

Each of the impacts identified here are difficult to measure using indicators. Nevertheless, the method should allow for the inclusion and qualitative description of such impacts in assessments of sustainability performance. None of these impacts should significantly affect the relative sustainability performance of the electricity generation systems as measured by the qualitative indicators reported in Chapter 5.

6.2.4.4 Scope of the Assessment

The sustainability assessment aims to compare electricity generation systems consuming Australian fossil fuels (see Section 1.2, Chapter 1). As the indicators describe Australian average electricity generation systems, individual systems are likely to have different sustainability profiles. The use of uncertainty and sensitivity analyses

enables an appraisal of the upper and lower limits of indicators for these individual systems. Used within Australia are other types of electricity generation technology, including cogeneration (for example, Morwell, Vic.), fluidised bed (Redbank, NSW), many internal combustion engine systems (private), hydroelectricity and solar and wind electricity generation. These systems, apart from hydroelectricity (8.6 % in 1997/98, Electricity Supply Association of Australia (1999)), produce very little of the total electricity generated annually. Therefore, the domestic systems (BIC, BrC and NG) examined are generally representative of the bulk of Australia's electricity generation systems.

The export systems (BICE and LNG) assume that the foreign generation and transmission subsystems are identical to those within Australia. However, this assumption is not accurate in all cases. For example, BICE consuming electricity generation systems in Japan use flue gas desulfurisation to reduce AD. Some foreign generation systems also treat flue gas for NO_x, thus improving AD, PS, EU, HT and ET impacts. Consequently, the export system indicators are less representative of actual performance than are the domestic system indicators. The export systems are likely to have improved environmental indicator scores, but worse economic indicator scores (due to the additional I and O & M for the desulfurisation and NO_x flue gas treatment equipment).

The assessment includes within the total system boundary impacts from generating electricity overseas with exported Australian fossil fuels. The assessment compares the impacts on sustainability caused by consuming Australian fossil fuels in different ways, without seeking to apportion responsibility between fuel supplier (Australia) and electricity generator (foreign) for respective impacts.

6.2.4.5 Substitutability of Electricity Generation Systems

This sustainability assessment method compares the performance of average electricity generation systems. Section 6.2.2 discusses options for replacing systems with poor indicator scores with other systems with better indicator scores. This assumes that such system replacement is feasible. Using this assumption, CCGT-NG systems, which have best scores in most categories, would increase their share of production. Yet, the assumption of substitutability may not be valid in many cases, because of a number of constraints. This section discusses these constraints on the substitutability of electricity generation systems.

There are limitations in both the amount of NG resources available and their delivery. At the consumption rates of 1999/2000, Australia had reserves for 105 years (AGA (2001))[§]. In comparison, Australia had reserves of BIC and BrC, at the consumption rates of 1997/98, for 258 and 744 years respectively[**] (ABA (2001)). Conversion of all electricity generation systems to CCGT-NG would reduce the NG reserve to 55 years[††]. This estimate excludes recent and planned expansions of LNG and other natural gas intensive exports, the possible use of natural gas as a source of hydrogen, and assumes that electricity demand does not increase, which would further erode this value. Complete depletion of Australia's resources of NG would require importation of LNG (if available) or could demand more difficult and expensive NG extraction and transportation strategies (such as, the pipeline transportation of gas from Western Australia to the eastern states). Both of these would substantially worsen the sustainability performance of electricity generation (see Figure 5.5.1, Chapter 5 for LNG case)[‡‡]. On a world scale, while BIC and BrC coal reserves are sufficient to provide electricity at any rate of consumption for centuries, NG reserves are much lower, but sufficient at current rates for several decades[§§] (IAEA (2000)). Thus, worldwide conversion of electricity generation systems to CCGT-NG may cause NG supplies to fail sooner than predicted (Hammond (2000), IAEA (2000), IChemE (2002b)). Even before its eventual depletion, as other nations deplete their domestic supplies of NG and become more dependent on imports, the price of NG will increase, and thus affect the economic impacts on sustainability for NG consuming systems (IChemE (2002b)).

The transport of NG from mining to generation subsystems is by pipelines. Pipeline

[§] These ratios are notoriously unreliable, and often drastically underestimate true resource life, as the resource base of the planet is not well defined (Hammond (2000)). For example, the resource life of oil from Bass Strait has increased from 20 to 23 years over the last 5 years (NRE (VIC) (2000)).

[**] These are underestimates as they include only reserves currently expected to be profitable. Under the same assumptions, NG resources will last only 48 years.

[††] This value is an estimate based on natural gas consumption and reserves from AGA (2001) (Table 2.10), electricity generation by fuel statistics in Electricity Supply Association of Australia (1999), and system natural gas consumptions from this work (see Section A2.5, Appendix 2).

[‡‡] This is also true for depletion of BIC and imports of BICE (Figure 5.5.1, Chapter 5).

[§§] Estimates vary from 40 to 70 years (Hammond (2000)).

projects in Australia presently have uncertain paths to gain approval for their construction (Ministerial Council on Energy (2002)). Consequently, there is little certainty in new pipeline projects to increase NG supply to major centres on the east coast of Australia. Therefore, as CCGT-NG plants are major NG consumers and usually close to major centres, there are no large CCGT-NG plants on the east coast, nor are there proposals for new plants. Equation 4.3.44 and Equation 4.3.46 (Chapter 4) indicate that the capital and operating costs of pipeline transport increase with distance, L, for the same NG delivery (Q and P). For example, in the ST-NG 1.47 Mtpa of NG delivery is over 927 km, for capital cost of \$ 234 million (AUD 2000). Doubling this distance, to 1854 km, increases the capital costs to \$ 389 million (AUD 2000). Consequently, the economic indicators of sustainability will worsen, and the average price of natural gas may have to rise to ensure the profitability of natural gas transportation.

If the replacement generation system is to be a coal system fuelled by a different coal (e.g. a BIC system replacing a BrC system) then there are two options. The first is to locate the replacement system near its resource and deliver electricity with new transmission lines. This may result in the need for very long transmission lines (e.g. from BIC mines in NSW to Victoria). Yet, transmission losses, and consequently the environmental effects per unit of delivered electricity, increase substantially with distance. Thus, these transmission losses may negate the improvements obtained by switching fuels. As with NG transport, it may be difficult to obtain approval such a project (Ministerial Council on Energy (2002)). The alternative option is to locate the replacement system at the location of the replaced system. This will extend the transport subsystem. Should that fuel be BIC, a comparison of the scores for BIC and BICE systems (Figure 5.5.1, Chapter 5) indicates that the use of domestic quality, BIC would be preferable over BICE. Critically, should that fuel be BrC, its transport over any great distance is uneconomic. Thus, for BrC only the first option is available. To compare the actual sustainability impacts of these options, modifications to the electricity generation systems presented would be necessary.

Replacement of any system because of its sustainability performance is difficult in privately owned electricity generation networks as there is no incentive for investment to improve performance (IChemE (2002b)). In Australia, as in the U.K. (IChemE (2002b)), the oldest systems have lowest debt, can sell their electricity to the market at lowest cost, and thus dominate. These plants generally have worst impacts on environmental sustainability. Thus, for Victoria, NG use was for about 8 % of electricity requirements in 1995, before full privatisation (Victorian Government (2001)). However, in 1999, after privatisation, only 0.2 % of electricity used NG (Victorian Government (2001)). The remainder was BrC use in ST-BrC systems, which had worse environmental impacts, but lower costs. Compounding the effect, the owners of these systems have no incentive to improve performance, as it requires investment capital (for plant improvements or development and proving of new technologies), and would increase their costs (Matthes and Timpe (2000)). For example, Section 6.2.2.2 shows the IGCC-BrC system as a substantial improvement over ST-BrC systems. Yet, substantial capital investment is required to advance the coal drying (MTE) and IGCC technology to commercial scale. The result of these influences is an electricity generation network providing electricity at lower costs to consumers. Under these conditions, new systems will have low profitability and thus there is no incentive for investment in them (IChemE (2002b)). The United Nations (2002) recognise these problems and recommends the removal of these impediments to improved sustainability. The difficulty lies in achieving this in a competitive electricity market, where governments should not apply direct regulatory control (IAEA (2000)). IAEA (2000) suggests: 'price controls, taxes, tradeable emission permits, development and transfer of advanced electricity generation technology, and directed research and development funding schemes' as methods for governments to achieve sustainability goals.

The operating costs exclude governmental taxes, on resources and company profits (see Section 3.3.3.4, Chapter 3). Taxes are uncertain sustainability impacts as they are dependent on many variables, including resource type (different tax rates apply for BrC, BlC and NG) and location (different states apply different tax rates). Moreover, taxes have both a negative sustainability impact on operators, by decreasing profitability, and positive sustainability impact on society, when spent on social welfare services, such as health, education, housing, etc. Including taxes may affect the relative economic sustainability performance of the systems.

6.3 THE SUSTAINABILITY ASSESSMENT METHOD

6.3.1 Overview of the Sustainability Assessment Method

This thesis has developed a sustainability assessment method with many new and enhanced features. Its basis is the use of individual indicators to measure each type of impact on sustainability. The method incorporates uncertainty and sensitivity analysis, and normalisation tools designed for use in other assessments. This section discusses the applicability of the use and integration of these methods to assessment of the sustainability of electricity generation systems.

Section 6.3.2 discusses the effectiveness of the indicator method in assessing the sustainability of electricity generation systems. The chosen indicators dictate the effectiveness of an indicator method. In the assessment, more than one indicator represents some of the impacts on sustainability. Section 6.3.3 discusses the indicators chosen for the method. Section 6.3.4 discusses the suitability of the sensitivity and uncertainty methods for the sustainability assessment method. Section 6.3.5 discusses the use of normalisation both as a method for presenting results and for assessing the relative sustainability of electricity generation systems.

6.3.2 The Indicator Method

Section 6.2 shows that the developed method measures impacts on sustainability, and compares the relative sustainability of different options and the relative importance of different impacts on regional sustainability. However, the method neglects some impacts known to be important to these systems, but difficult to quantify (Section 6.2.4.3). Modification of the method is necessary to include these impacts in evaluations of sustainability performance.

Section 2.3.2 (Chapter 2) identifies other methods for sustainability assessment. Applications of these other methods for sustainability assessment have been to dissimilar systems, limiting opportunities for direct comparisons. Application of the developed sustainability assessment method to these dissimilar systems may allow verification of this method and realisation of its advantages and disadvantages.

6.3.3 THE INDICATORS

Multiple indicators in Chapter 5 represent some of the impacts identified as important to electricity generation systems. For example, the HT, ET, LTI and Fatal indicators represent different aspects of the 'toxicity' and 'health and safety' impacts: HT on the health of humans (employees and the general population); ET on the health of plants and animals***; and LTI and Fatal on the safety of employees.

The RD W, RD A, EN and EX indicators represent the 'resource depletion' indicator category. This category indicator is important for fossil fuel electricity generation systems as they consume large quantities of fossil fuels. The category indicator attempts to measure the impact on sustainability of consuming materials now, and thus limiting their availability in the future. Thus, it should include: present resource scarcity and the needs of the future for that resource. Yet, estimating the needs of the future is problematic: planners have difficulty estimating needs for even a few decades†††. Sustainability assessment requires estimation of the needs of people many generations into the future (50-100 years). Thus, present methods are measures of resource scarcity. EN is a measure of the energy resources consumed by the process. It is an un-weighted measure, assuming that all fuels are interchangeable (energy is energy no matter the source). However, BrC systems cannot consume low moisture content fuels like NG or BlC (see Section 6.2.2). Similarly, NG systems cannot burn solid fuels like BrC or BlC, and the mining and transport equipment present in all systems cannot suddenly switch their fuel, from say diesel to BrC. Furthermore, it does not account for the relative scarcity of particular resources and excludes non-energy resources. While, in electricity generation systems non-energy resource consumption is minor, other types of systems may consume large quantities of such materials. Thus, EN is an incomplete measure of resource depletion. EX is an advanced energy measure, which estimates the loss of useful energy when consuming resources. Its advantages over EN include the ability to include other resources and differentiate between different types of energy sources. The inclusion of other resources is by estimation of the lost useful energy

*** Section 4.4.6, Chapter 4 explains the exclusion of HT and ET from the sustainability performance discussion (Section 6.2.2) for these systems.

††† The State Electricity Commission of Victoria, for example, predicted in 1976 that demand in 1992 would reach 52500 GWhpa, with a peak demand of 9600 MW (SECV (1976)). The actual demand in 1992 was 39109 GWhpa, with a peak demand of 6005 MW (SECV (1993)).

during their production. Unfortunately, these values change with time, as the technology for the production of resources develops. In spite of these additional benefits, like EN, EX is a measure of resource consumption, not resource scarcity. The RD W and RD A indicators are both measures of resource scarcity. Each indicator applies the same method, but the information used to generate equivalence factors (CF) factors for RD W is global, while for RD A it is Australian (see Equation 3.2.1, Chapter 3). The RD W and RD A indicators for electricity generation systems have substantially different scores (see Figure 5.5.1, Chapter 5). Section 6.2.2 attributes this difference to Australia's high level of resources, in comparison to its consumption rates. Comparing the regional (RD A) and world (RD W) indicators and expressing them as a ratio (Table 6.3.1), allows estimation of the possibility of future dependence on resources from outside the region. This indicates that LNG systems have highest probability of being the first type of system requiring resources from outside Australia, and BrC systems have lowest probability. Thus, both of these indicators have merits that necessitate their inclusion.

Table 6.3.1: Ratio of RD A to RD W to show the relative probability of Australia requiring to import fossil fuels for each of the electricity generation systems (RD A and RD W from Figure 5.5.1).

Fuel	Technology	Ratio
BlC	ST	0.0147
	IGCC	0.0174
BlCE	ST	0.0719
	IGCC	0.0682
BrC	ST	2.24×10^{-3}
	IGCC	2.24×10^{-3}
NG	ST	0.118
	OCGT	0.121
	CCGT	0.121
LNG	ST	0.204
	OCGT	0.206
	CCGT	0.206

Section 6.2.2 assumes that if a system has lower RD A scores than RD W scores, its resource consumption is of lower importance to Australia than the world. Yet, this assertion ignores the fact that Australia is dependent on imports of other resources (such

as crude oil). Australia exports its abundant resources to fund the importation of scarcer resources. Consequently, consumption of any Australian resource is important.

The AC, VA and CVA indicators represent the 'wealth generation' indicator category. In the sustainability performance discussion (Section 6.2.2) I is proven important, but VA excludes I. Thus, while VA indicates that CCGT-NG systems provide less wealth than BrC and BlC systems, both indicators that include I, AC and CVA, indicate BlC systems to provide least wealth. Thus, the CVA indicator is important to ensure inclusion of these capital-related effects. The AC indicator is also an indicator of wealth generation, but it includes I and labour costs. Thus, it is a more complete indicator of wealth generation than either VA or CVA. However, AC is only an indicator of wealth generation because of the assumption that the value of electricity sold from each system is equivalent. When this assumption is inaccurate, then net present value is more appropriate. Nevertheless, each of the included indicators provides unique information about wealth generation performance.

The ED and EI indicators represent the 'employees' indicator category. ED indicates the numbers of employees directly employed by the system. High ED is a positive social impact in one sense, spreading wealth generated widely. Alternatively, high ED may count as a negative economic indicator, reducing the system's wealth generation. EI indicates the numbers of employees whose employment occurs because of the system. It thus includes: employees of contractors, employees of companies selling materials and services to the industry, and employment generated through their spending. EI is thus a more apt measure of the employment impact of these systems. Nevertheless, producing EI uses industry wide averages, and thus may not accurately estimate the EI that occurs for these systems. For example, the EI factor for the generation subsystems, 'Electricity', does not differentiate between BrC, BlC and NG systems. These systems have vastly different numbers of employees for their output (see Figure 5.5.1, Chapter 5). Nor does the 'Electricity' factor differentiate between the generation or transmission subsystems[‡‡‡]. Thus, the reported EI scores are less certain than are ED scores. Therefore, when presenting EI indicator scores, ED and EI scores should both appear.

[‡‡‡] It also includes distribution of electricity.

6.3.4 UNCERTAINTY AND SENSITIVITY ANALYSIS

Data quality assessment is important for the development and acceptance of LCA as a decision-making tool (see Section 3.2.3.7.1, Chapter 3). It is also important for sustainability assessment, as the method uses LCA to estimate environmental indicator scores. Yet, assessments of data quality are rare, and there is no consensus on the appropriate methods to use. Each of the methods tested indicates greater uncertainty in the black coal system results than in the brown coal system results. The Monte-Carlo method (see Section 3.2.3.7.2, Chapter 3) enables a single uncertainty range to be reported for each environmental impact result, allowing the results to be presented using standard quality assessment tools (i.e. box plots). The use of the normalised difference probability distribution plot, enables quantification of the difference between two systems if their uncertainty ranges overlap (see Figure 5.2.2, Chapter 5). The qualitative methods enable tracing of the source of this difference to the greater usage of data derived from plant measurements for the brown coal case. The two combinatorial methods, Kennedy *et al.* and Meier, produce very different results (see Table 5.2.6, Chapter 5). There is no evidence that either approach produces results that are more accurate, or more representative of qualitative uncertainty, than is the other. Moreover, as they are reliant on subjective (expert) reasoning, neither method produces a measure of uncertainty that is more relevant than that of the numerical uncertainty method alone. These methods provide no greater information than the quantitative methods, and present far less information than the qualitative and quantitative methods presented separately. Therefore, uncertainty assessments should present results from both numerical and qualitative assessment methods separately.

The use of the Monte-Carlo method shows that different results occur when using different types of uncertainty distributions (see Table 5.2.2, Chapter 5). In the case of the AD indicator for ST-BrC systems, the use of triangular and uniform distributions worsens the mean impact value by over 300 %. The uncertainty distributions of the NO_x and SO_2 emissions, which are the major contributors to AD, are highly skewed, i.e. their mean and minimum values are similar, and distant from the maximum value. This is approximately a log-normal distribution (see Figure 3.2.2, Chapter 3), and neither the uniform or triangular distributions can successfully approximate log-normal distributions. The mean of a uniform distribution must lie halfway between its extents. The mean of a triangular distribution is limited such that its average must lie between 29

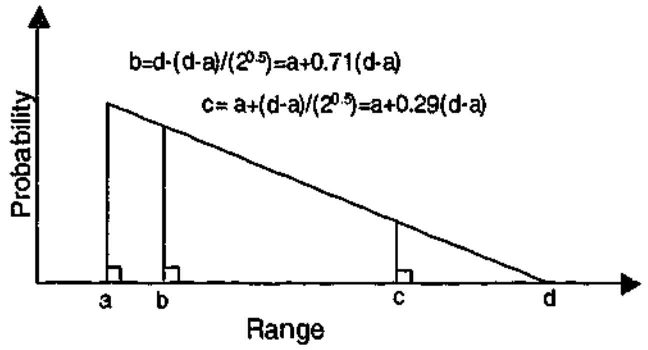

Figure 6.3.1: The maximum and minimum positions for the mean of triangular distributions. Positions of b and c calculated using laws for similar triangles and equal probabilities (area left and right must equal half).

and 71 % of the distance between its extents (see Figure 6.3.1). The fact that such problems can occur, limits the practicality of standard, arbitrary distributions. When estimates for the distribution of each data point are not available (i.e. insufficient data), then the use of a skewed distribution, such as the triangular or log-normal distributions is recommended. They allow the average data point to be closer to either its minimum or maximum, and require only a data point's average, minimum, and maximum values (see Figure 3.2.2, Chapter 3). The triangular distribution probably overestimates the true uncertainty profile (a skewed normal distribution) and thus provides a conservative estimate.

Of the tested qualitative methods, neither weights quality scores by contributions to the indicator score[§§§]. Thus, their scores are indicative of the quality of the data collection methodology (i.e. how good relative to theoretical perfection), not of the quality of the indicator scores. Nevertheless, the Rousseaux *et al.* method does allows the location and identification of the causes of deficiencies in data quality. As such, neither method's results indicate the quality of the environmental impact results. The comparison of these qualitative methods may be unfair as both methods recommend the inclusion of other indicators in their intended indicator sets.

6.3.5 NORMALISATION AND PRESENTATION OF INDICATOR RESULTS

The aim of normalisation is to enhance understanding of the relative importance and

[§§§] The method of Lindeijer *et al.* (see Berg *et al.* (1999)) reportedly does this, however evaluation of this method is difficult as it is only available in Dutch.

magnitude of the indicators (see Sections 3.2.3.5 and 3.5, Chapter 3). Much of the sustainability performance discussion (Section 6.2.2) requires only the pre-normalised indicator scores (of Sections 5.2, 5.3 and 5.4, Chapter 5). For example, pre-normalised scores allow comparisons of the relative performance of systems for particular indicators (i.e. the CC score for ST-BIC systems is better than the CC score for ST-BrC systems). However, pre-normalised scores cannot provide indications of the relative importance of a system's performances for different indicators. For example, is the CC score for ST-BIC systems better or worse than its AD score? The normalised scores describe importance to the Australian regional sustainability by providing an appreciation of relative performance in different categories. Establishing that the importances of any two indicators are different is problematic, as the normalised scores are not strictly indications of the relative severity of the impacts. Thus, a difference is only significant if there are large, order-of-magnitude differences between the indicators (i.e. 10^8 and 10^9).

The validity of the comparison of normalised economic and social indicators with environmental indicators is not established. If this method can compare completely different types of environmental types of impact, such as CC and RD W, then it is equally acceptable to compare different types of sustainability impact. This is the first time to the author's knowledge that normalisation has been used to compare environmental, economic and social impacts.

Another method to try to enhance understanding of the indicator results is weighting (see Section 3.2.3.5, Chapter 3). Weighting relies on subjective, value judgements to assign importance to the magnitude of each indicator's score. It is important that the use of value judgement does not undermine the value of the quantitative, scientifically based work up to this point of decision making.

6.4 POTENTIAL APPLICATIONS OF THE SUSTAINABILITY ASSESSMENT METHOD

6.4.1 OVERVIEW OF POTENTIAL APPLICATIONS OF THE SUSTAINABILITY ASSESSMENT METHOD

The developed method assesses the impact on sustainability of electricity generation systems. This data may have other important uses. For example, where a company, or network operator, desires to provide a new electricity generation system, in a sustainable manner, the method guides the choice of the most appropriate technology for this goal. Similarly, electricity consumers may desire to select the most sustainable electricity supplier, from a choice of different electricity generation systems. Measurements of impacts on sustainability may also be of use for other systems.

Section 6.4.2 discusses the potential for the use of the method in the planning of electricity supply systems. Section 6.4.3 discusses the potential for the use of the method by electricity consumers. Section 6.4.4 discusses the potential application of, and limitations in, using the method for systems other than electricity generation systems.

6.4.2 ELECTRICITY SUPPLY PLANNING

Traditional approaches to the planning of electricity supply attempt to meet anticipated demands of consumers, reliably and at lowest possible cost (IAEA (2000)). This requires development of an electricity demand forecast and a capital works budget and schedule to meet this forecast. Government owned electricity supply networks would produce these internally. In deregulated networks, governments develop forecasts, but private companies own and develop the electricity generation network. In these networks, governments must ensure that forecast electricity supplies are met, through legislation or other means (IAEA (2000)). Inclusion of environmental concerns in previous planning methods has been by costing measures to achieve regulated limits on emissions (IAEA (2000)). Consequently, optimisation of existing electricity supply networks has been for low electricity costs (i.e. the AC indicator), which is only one type of sustainability impact. Emerging planning methods are using pricing incentives to attract investors and customers to renewables, such as the MRET scheme in

Australia, which have their own problems (for example, see Ministerial Council on Energy (2002)). Using the presented sustainability assessment method, electricity supply planning could integrate all sustainability impacts known to be important for electricity generation systems.

Electricity supply plans generally modify networks in three ways:

1. Addition of new electricity generation plant;
2. Replacement of existing plant; and
3. Acting to reduce demand.

When considering the addition of a new electricity generation plant, the first step is to identify possible options. Sections 4.2.2.3, 4.2.3.3 and 4.2.4.3 (Chapter 4) discuss the most likely options for new power stations within Australia. The use of the sustainability method enables the estimation of the probable sustainability impacts of each choice as sets of indicators (see Figure 5.5.1, Chapter 5). The basis for selecting an option can now be the sustainability performance (see Section 6.2). Alternatively, the planners may require certain performances for particular impacts, but consider some other impacts of little consequence. The assessment may include these biases by weighting the indicator scores appropriately. For example, a planner may consider low climate change emissions and low electricity costs to be of greatest importance, and resource depletion and employment of low importance. In this example, high weightings will apply to the CC and AC indicators, and low weightings to the RD W, RD A and ED indicators. However, conclusions based on these weighted results will be debatable, as these weighting schemes have no scientific basis (see Section 6.3.5).

An alternative basis for these assessments might be the minimisation of network sustainability impacts. The electricity generation network consists of a number of electricity generation plants, and thus electricity generation systems. The sustainability indicator scores for the network will equal the sum of sustainability indicator scores from using this method on each of the systems, weighted by their respective electricity generation. For example, a network consisting of a ST-BlC system (CC score = 1060 kg $CO_{2\text{-eq}}$ per MWh) producing 30 GWh of electricity, a ST-BrC system (1210) producing 15 GWh and a CCGT-NG (458) system producing 10 GWh will have a CC score of approximately 991 kg $CO_{2\text{-eq}}$ per MWh (scores from Table 5.2.1, Chapter 5). If the existing network has poor scores for some indicators, the basis for choosing between options could be to minimise additional, or reduce, contributions to this indicator score.

Periodically network planners replace older electricity generation plants with new plant. In this case, impacts on sustainability usually decrease, as new plants normally have higher efficiencies than those replaced. Yet, this may not be so for all such replacements and for all sustainability impacts. For example, consider the replacement of an average ST-BrC plant with a ST-BlC plant. Section 6.2.2 discusses such a replacement in the context of ameliorating the CC impact, and shows that while this change improves some indicator scores, it worsens many more. The same assessment highlights that replacement with a CCGT-NG improves most indicators. This option may be a better choice on sustainability grounds. An additional benefit of the method is that it allows quantification of the scale of improvements, or deteriorations, in impacts caused by the change. For example, using the previous example, the change in CC score for replacing a ST-BrC system (CC score = 1210 kg $CO_{2\text{-eq}}$ per MWh) with a ST-BlC system (1060) is 150 kg $CO_{2\text{-eq}}$ per MWh, or 12.4 % of the old CC score.

The last type of change is demand reduction. Reducing demand involves improving the efficiency at which end users consume electricity. Governments operate many schemes to improve the energy efficiency of consumers, and industries often attempt to improve their energy efficiency to reduce electricity costs, albeit often at the expense of increased capital costs. Estimation of the quantitative improvement in sustainability caused by reductions in demand requires an estimate of the sustainability impacts of electricity consumption. The sustainability assessment method can produce such an estimate: the electricity generation network's sustainability indicators. The product of these indicators and the reduction in energy demand is a measure of the improvement in sustainability performance. For example, if demand for electricity from a network containing a ST-BlC, ST-BrC and ST-NG, with a CC score of 991 kg $CO_{2\text{-eq}}$ per MWh (see earlier example), is reduced by 100 MWhpa, then the reduction in CC is 9.91×10^4 kg $CO_{2\text{-eq}}$ per annum.

It may be of benefit when using this method for electricity supply planning to introduce an indicator of supply reliability. The current indicator is usually reserve (or peak reserve) capacity, and this may serve. However, this measure does not account for the likelihood of an individual system to fail. For example, older plant more often fails than newer plant. Another factor may be the propensity of workers to call for strike action. A complete reliability indicator could include these and other factors in its

measure.

6.4.3 Optimum Electricity Source Planning

Operators of electricity generation networks could use the sustainability method to estimate and trade-off sustainability impacts. Electricity generation networks, like Australia's National Energy Market, source electricity from many different types of plant. The total sustainability of the network will depend on the proportions of electricity sourced from each type of plant****. This method allows quantification of the relative impact on sustainability when deciding between two different types of plants for any amount of electricity. For example, an operator requires 100 MW, which is available from either ST-BrC (CC score = 1210 kg $CO_{2\text{-eq}}$ per MWh) or CCGT-NG systems (458) (scores from Table 5.2.1, Chapter 5). Thus, the choice of the CCGT-NG system rather than the ST-BrC alternative negates 7.52×10^4 kg $CO_{2\text{-eq}}$ per MWh of CC impact. These quantities could be of use as guides for trading impacts. For example, if electricity from a ST-BrC system is available at a lower cost than electricity from a CCGT-NG system, then the operator can quantitatively compare differences in cost and sustainability. Trading impacts may limit the magnitudes of individual impact magnitudes, by ensuring a wide range impacts, rather than great amounts of a few††††.

6.4.4 Applicability to Non-Electricity Systems

The sustainability method, although developed for electricity generation systems, is flexible, allowing the quantification of impacts from any fossil fuel electricity generation system. The basis for the choice of indicators for this method is that they must measure an impact known to be important for electricity generation systems. Consequently, the indicators in Chapter 5 are applicable only for systems whose important impacts align with those of electricity generation systems. Fortunately, many systems have this characteristic. Examples include non-electricity natural gas delivery, petroleum fuels and products, steel and other metals, chemicals, fertilisers, and plastics

**** Section 6.4.2 describes the procedure for estimating the sustainability of an electricity generation network

†††† IAEA (2000) uses a similar argument for limiting environmental impacts by using a greater diversity of electricity sources

manufacturers. For some of these systems, additional impacts may occur which the methods indicators do not measure (c.f. Section 6.2.4.3). The sustainability assessment method is flexible and can include additional indicators for those impacts as appropriate.

One simple example of an application using other systems is to include other types of electricity generation systems (oil, nuclear, renewables). Such an analysis would enable the widening of the analyses in Sections 6.2, 6.4.2 and 6.4.3 from the most probable options to all possible options.

Another example is to use the analysis for all types of systems consuming large amounts of one resource. For example, apart from electricity generation, the production of many chemicals, such as hydrogen, methanol, ammonia, urea and other fertilisers, consume large amounts of NG. The analysis would enable the quantification of the relative sustainability impacts of each consumer of the resource. Such information could aid in resource use planning by governments, or companies with interests in multiple consumers of the resource.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 OVERVIEW OF THE RESEARCH FINDINGS

7.1.1 THE SUSTAINABILITY OF ELECTRICITY GENERATION SYSTEMS

The indicators of sustainability of electricity generation systems indicate no one type of system has worst environmental or sustainability indicator scores for every indicator. Thus brown coal is not a 'dirtier fuel' than black coal and natural gas using a basis of either overall environmental or sustainability performance. The normalised indicators, normalised using newly developed Australian indicator scores, are mostly of similar magnitude. Nevertheless, capital expenditure (I) is clearly of a higher magnitude and thus most important for the Australian region. Consequently, while climate change (CC) deserves inclusion in decision-making processes, so too do the other impacts on sustainability.

The electricity generation systems consuming brown coal (BrC) do not have worst indicator scores in all categories. A major advantage of BrC is its economic performance. BrC systems have low electricity costs and high value added. However, the investment costs of BrC steam turbine systems are very great. The electricity generation systems consuming BrC outperform those consuming black coal (BlC) for the majority of indicators. The acidification (AD), solid waste (SW), and worker injuries (LTI) and fatalities (Fatal) indicator scores for BlC systems are particularly poor. The electricity generation systems consuming natural gas (NG) in combined cycle gas turbine (CCGT-NG) systems are the most sustainable of the considered systems. The performance of open-cycle gas turbine (OCGT-NG) and steam turbine (ST-NG) systems is significantly worse than these CCGT-NG systems. Therefore, the conversion to, or replacement with, CCGT-NG systems of existing systems with these configurations should be a priority.

While, CCGT-NG systems are the best option of the systems considered, the reserves of Australian natural gas are substantially less than the coals. Thus, the consumption of natural gas has greater relative impact, as measured by the newly developed Australian resource depletion indicator (RD A), than the consumption of the coals. Furthermore, constraints in the addition of new gas transport pipelines limit the rapid expansion of natural gas consumption which conversion or replacement of coal systems to gas would require. The use of advanced electricity generation technology for the coal systems has substantially greater sustainability than the conventional technologies. However, advanced technologies are not commercially available at present for either of the coals.

Foreign electricity generation from natural gas (LNG) and black coal (BICE) exported from Australia is less sustainable than domestic electricity generation, due to the need to prepare and transport the fuels over long distances. Of the options, the CCGT-LNG systems are most sustainable. However, as for domestic NG systems, consuming natural gas resources to produce LNG has relatively greater resource depletion impact, as measured using RD A, than the consumption of black coal.

Uncertainty and sensitivity analyses show that the ranking for the systems, using the sustainability indicators, is robust to data uncertainty and decisions made during the formation of the indicators. Nevertheless, an analysis of data uncertainties indicates that it is possible for the relative climate change (CC) performance of BrC and BIC steam turbine (ST) systems to reverse under specific circumstances. However, the normalised difference uncertainty method shows, in an objective manner, that there is a higher probability of the ST-BIC system having better CC performance than the ST-BrC system, than the reverse situation.

The uncertainty analysis tests several methods for estimating the magnitude of uncertainty in the indicators due to uncertainties in the data used in their production. All methods show that the climate change, acidification and world resource depletion indicators (RD W) of the ST-BIC system have greater uncertainty than the corresponding ST-BrC indicators. The qualitative methods establish that the greater use of data derived from plant measurements for the ST-BrC systems cause this difference. Uncertainty in electricity efficiency has greatest influence on the values of the indicators, and thus a sensitivity analysis using this efficiency can estimate the effect of data uncertainty on electricity generation systems. The sensitivity analysis shows that decisions such as the method to allocate impacts between products, transport destination (for export systems) and assumed system size (estimated by capacity) have considerable influence on the sustainability indicator scores.

7.1.2 About the Sustainability Method

The developed method allows production of indicators for all impacts on sustainability identified as important for electricity generation systems consuming Australian fossil fuels. Important features of the method are its ability to provide quantitative indicators, use of a scientific basis for quantification of environmental impacts and accommodation of the 'life-cycle' perspective. Including only the electricity generation subsystem would significantly reduce the importance of some indicators, such as the BIC and BICE systems' worker injuries and fatalities indicators. The method can compare the sustainability performance of systems with different combinations of fuel and electricity generation technology.

The developed method allows estimation of the relative magnitude of each impact on regional sustainability, through normalisation. The application of normalisation to economic and social indicators is uncommon and environmental normalisation factors from authoritative sources for Australia are not available. Thus, the use of normalisation required the estimation of new normalisation factors for Australia using diverse sources of Australian material, economic and social flows data. Normalisation does not involve non-scientific methods (c.f. weighting) to attach 'importances' to each indicator. However, normalisation provides an objective method for assessing the relative magnitude of contributions to different types of sustainability impact.

The EN and EX indicators are not necessary for the quantification of the resource depletion impact on sustainability as they do not measure resource scarcity. RD A, a new Australian based indicator of resource depletion, can show both Australian resource scarcity and, together with RD W, differentiate between Australian and worldwide resource scarcity.

Analysis of the robustness of the indicators to data quality assessment is important for the development and acceptance of LCA as a decision-making tool. Yet, the use of data quality assessment in published LCA studies is rare, and there is no consensus on the methods to use. The Monte-Carlo method produces a single uncertainty range for each environmental indicator. When knowledge of a data source's numerical uncertainty profile is unavailable, the uncertainty analysis findings recommend the use of a skewed distribution (such a the triangular or log-normal distributions). The qualitative methods, such as that of Rousseaux *et al.*, can link differences in the magnitude of uncertainty in the indicators of different systems to the types of data used to estimate their indicators. The methods that combine numerical data uncertainty with quantitative uncertainty in a single uncertainty measure are reliant on subjective (expert) reasoning, provide no additional information and present far less information than if the qualitative and quantitative methods are presented separately. Therefore, when an uncertainty analysis is necessary, the best approaches currently available are the Monte-Carlo method (quantitative) and Rousseaux *et al.* (qualitative) methods. As the methods for data quality assessment are still underdeveloped, uncertainty analysis is recommended only where the differences between the options is debatable and the choices have impacts of considerable magnitude.

7.2 LIMITATIONS OF THE RESEARCH

7.2.1 OF THE SUSTAINABILITY OF ELECTRICITY GENERATION SYSTEMS

The sustainability assessment relies on a number of assumptions, which may influence the magnitudes of the sustainability indicators. Firstly, the system boundary excludes secondary processes (such as construction), as others have reported their contributions as minor, and is thus not strictly compatible with the 'life-cycle' perspective. The data collection excludes some environmental data, as reliable emissions data for certain species is unavailable, necessitating the exclusion of toxicity impacts from the discussion of sustainability performance. Difficulties in quantifying some effects with indicators resulted in the exclusion of some impacts identified as important for electricity generation systems. The assessment assumes that the electricity generation systems consuming the exported Australian fuels (LNG and BICE) have electricity generation and transmission systems characteristic of Australian systems, rather than their own systems. Finally, the scope of the assessment is average Australian electricity generation systems, and thus the sustainability profiles for individual systems or for similar systems in other countries, may have minor differences.

7.2.2 OF THE SUSTAINABILITY METHOD

While the method attempts to select indicators for each impact important to electricity generation systems, some impacts are difficult to quantify with indicators, such as the

effect of subsidence. The method allows the inclusion of qualitatively measured impacts through discussion, but does not provide a generalised procedure.

The validity of using normalised scores for comparing economic and social impacts with environmental impacts is not established, as no other workers have apparently used this method.

Section 3.2.3 (Chapter 3) identifies shortcomings of the method for producing environmental indicators (LCA). Of those noted, this work considers resource depletion, uncertainty analysis, normalisation and weighting. The presence of such difficulties may limit the accuracy of some of the environmental indicator scores.

7.3 RECOMMENDATIONS FOR FURTHER RESEARCH

The developed sustainability method is able to assess the sustainability of Australian electricity generation systems. Nevertheless, its application to a system, on which others have previously applied another sustainability assessment method, is necessary to verify the stated advantages of the method developed in this thesis.

The basis for the conclusions and recommendations of the uncertainty analysis is the data of only two systems (ST-BrC and ST-BIC) and three indicators (CC, AD and RD W). The conclusions drawn about uncertainty analysis rely on this basis (see Sections 7.1.1 and 7.1.2). Extension of the uncertainty assessment to all systems and indicators will test the validity of these conclusions.

The sustainability assessment method has no defined procedure for the integration of impacts, which are difficult to quantify, into assessments of sustainability performance (see Section 7.2.2). Development of such a procedure will enhance the value of the method and the sustainability performance assessments it produces.

Section 6.4 (Chapter 6) identifies a number of potential applications for the developed method. Tests of the method's ability to apply to electricity generation network supply and source planning can commence with the data contained in this thesis. However, testing of the method for assessing the sustainability of other systems (for example, oil, nuclear and renewable energy systems) will require further, time-consuming data collection.

APPENDICES

APPENDIX 1: DATA SOURCES FOR THE SUSTAINABILITY ASSESSMENT

A1.1 OVERVIEW OF DATA SOURCES FOR THE SUSTAINABILITY ASSESSMENT

Sections A1.3 to A1.5, detail the data sources behind the subsystem data given in Chapter 4. Section A1.3 details the data sources for systems consuming either domestic or export black coal. Section A1.4 details the data sources for systems consuming brown coal. Section A1.5 details the data sources for systems consuming natural gas or LNG. Section A1.7 details the data sources necessary to conversion of this data into sustainability indicators. Section A1.8 details the data sources for the fuel emission factors. Section A1.9 shows the data for the normalisation factors. Section A1.10 provides examples of the aggregation methods used to produce data from multiple sources.

A1.2 EXPLANATION OF TABLE TITLES

The tables presented in this appendix enable the duplication of the data shown in Chapter 4. Each table entry has a reference number ('Ref.'), which refers to its position in Chapter 4. The first part of this number is a letter, which indicates to which of the included technologies the data belongs. For example, in the black coal mining subsystem, A indicates the data is for underground mining and B for surface mining. The number following this letter indicates the data's position in the relevant table in Chapter 4. Indication of positional aspects such as system, subsystem, and type of data (material, economic or social), is by identical sub-sectioning in Chapter 4 and this appendix.

Entries in the second column ('Agg.') indicate which aggregation procedure is used to produce the data from the sources shown in the next column ('Sources'). Possible entries are:

- N (no aggregation);
- EN (estimated as negligible);
- YA (yearly average);
- FA (factored average);
- SA (simple average);

- PW (production-weighted average);
- CW (capacity-weighted average);
- MW (employment or employee hours-weighted average);
- FE (estimate obtained by applying a factor to another data value);
- WE (calculation built in parts using separate sources for each part);
- MC (solution of multiple linear, multivariate equations);
- R (estimate relying on ratios based on old data);
- EM (emission factor based calculation); and
- CP (correlation using power function).

Section A1.8 shows emission factors for the fuels encountered.

Some data sources contain multiple values for the desired data value. Entries in the fourth column ('S. Agg.') indicate which aggregation procedure is used to aggregate these multiple values. Possible entries are:

- N (no aggregation);
- YA (yearly average);
- RA (rolling average); and
- EC (economic correlation).

Section A1.10 provides further details and examples of these aggregation methods.

The final two columns, 'PM Scores' and 'Range', include data necessary to produce an uncertainty assessment on the BlC-ST and BrC-ST system's environmental indicators. The first column ('PM Scores') contains pedigree matrix scores (see Table 3.2.3, Chapter 3), where R, C, T, G and E are the reliability, completeness, temporal correlation, geographical correlation, and technological correlation indicator scores. The final column ('Range') contains the minimum and maximum values found for each data point. Superscript values in this column, and throughout this appendix, are magnitudes (i.e. ^{6} equals x 10^{6}).

A1.3 BLACK COAL AND EXPORT BLACK COAL

A1.3.1 Mining Subsystem

A1.3.1.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
C1	SA	DMR (2000), Alyward and Sutherland (2000), DME (1998) and DME (2000)	N	2	2	1	1	1	0	41.9
C2	FA	BHP (1999a), BHP (1999b), BHP (1999c), BHP (1999d) A, BHP (1998), BHP (1999e), BHP (1999f), BHP (1999g), BHP (1999h), BHP (1999i), Pacific Coal (1999) B	YA (U), SA (S).	1	2	1	1	1	14.3	21.8
C3	See C2			4	5	1	1	3	1.68^{4}	3.82^{6}
C4	See Section A1.4.1.1 A4			4	5	1	1	3	912	1370
C5	SA	Theodore Coal (1981), Spath *et al.* (1999), Tasman Asia Pacific (1997)	N	3	4	5	1	1	1.2^{6}	2.48^{6}
C6	N	Spath *et al.* (1999)	N	2	3	1	3	2	2.74^{5}	2.74^{7}
C7	PW	DMR (2000)	N	2	2	1	1	1	1.99^{6}	1.95^{7}
C8	N	Dharmappa *et al.* (2000)	N	2	2	1	1	1		
C9	PW	As in C2, Additional: Coal and Allied (1999) B		1	2	1	1	1	1.3^{7}	3.96^{8}
C10	See C7			2	2	1	1	1	1.99^{6}	1.95^{7}
C11	N	Mass balance								
C12, C14-C19	EM	Diesel, Petrol EM	N	3	5	1	2	3	8.00^{4}	1.09^{7}
									121	1.69^{4}
									2	312
									1123	1.57^{5}
									437	6.09^{4}
									227	3.18^{4}
									48	6473
C13	EM	Diesel, Petrol EM, and Smith and Sloss (1992), NGGIC (2000), Williams (1998) M	N	3	5	1	2	3	17.4	906
									2.95^{6}	4.08^{6}

A = Underground Mining, B = Surface Mining, C = Average Mine, M = Natural Emission from Exposure to Air.

A1.3.1.2 Economic Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	CP	Anonymous (2001a), DITC (1980-1986), Errington and Kirby (1993)	EC							
A2	CP	DOI (U.S.A.) (1993), ACCC (1986), EIA (U.S.A.) (2000), Errington and Kirby (1993)	EC							
B1	CP	NREC (1987), BHPBilliton (2001a), DITC (1980-1986), Macarthur Coal (2001), Mining Technology (2002)	EC							
B2	CP	DOI (U.S.A.) (1993), ACCC (1986), Tasman Asia Pacific (1997), Simes (2000), EIA (U.S.A.) (2000)	EC							
C1	FA	A1 and B1								
C2	FA	A2 and B2								

A = Underground Mining, B = Surface Mining, C = Average Mine.

A1.3.1.3 Social Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
C1	PW	Coal Services (2002), NRM (Qld.) (2001)	N							
C2	PW	NOHSC (2000)	N							
C3	PW	NOHSC (2000), MCA (2002)	N							

C = Average Mine.

A1.3.2 Transport Subsystem

A1.3.2.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
X1	SA	Aylward and Sutherland (2000), DME (2000), DMR (2000), confidential sources and estimates.		5	3	1	1	1	1	24
X2	SA	Spath *et al.* (1999), Szabo (1978)		2	3	1	3	1	16.1	29.9
X3	See X1			5	3	1	1	1	13.6	17.4
X4	See X1			5	3	1	1	1	115	900
X5	PW	Freightcorp (2000), Queensland Rail (2000)		1	1	1	1	1	3150	8645
X6	See X1			5	3	1	1	1	16.3	28.5
X7	See X1								1	11
X8	See X1								54.7	69.5
X9	WE	Productivity Commission (1998)	N							
X10	N	Productivity Commission (1998)	N							
X11	N	Woodside Energy Ltd. (1998)	N							
A1	N	Sazbo (1978)	N	2	2	5	3	1	0.044	2.46
A2	PW	Sazbo (1978), Woodside Energy Ltd. (1998) Rl, Szabo (1978) Rd	N	3	3	5	3	1	1.69^{5}	63.3^{5}
A3	WE	OECD (1985), Chadwick *et al.* (1987)	N	5	5	1	1	1	9.97^{8}	9.98^{8}
A4	See A3			5	5	1	1	1	8.94^{4}	1.31^{5}
A5-A11	EM	Diesel EM	N	3	5	1	2	3	5.28^{3} 43.2 818 15.2 7.62^{3} 2.96^{3}	1.98^{7} 1.62^{3} 3.07^{4} 568 2.86^{5} 1.11^{5}

									1.55^{3}	5.80^{4}
A12	EM	Diesel EM for particulates, see A3 for dust	N	3 5	5 5	1 1	2 1	3 1	314 8.94^{4}	1.18^{4} 1.31^{5}
B1	WE	Spath *et al.* (1999) for coal cleaning and ports.	N							
B2	See B15									
B3	WE	See A2	N							
B4	SA	Smit and Nieuwlaar (1994), Simapro 5 (2001)	N							
B5	N	Spath *et al.* (1999)	N							
B6	See B15									
B7	See B5									
B8-B14	See A5-A11									
B15	WE	See A12, additionally Smit and Nieuwlaar (1994) for ship transport, and Spath *et al.* (1999), Smit and Nieuwlaar (1994) for coal cleaning	N							

A1.3.2.2 Economic Flows

Ref.	Agg.	Source(s)	S. Agg.	R	C	T	G	E	Min.	Max.
A1	CP	Macarthur Coal (2001), Freebairn and Trace (1988), Easton (1988), CFAC (Ill.) (1977)	EC							
A2	CP	CFAC (Ill.) (1977)	EC							
A3	CP	Lee (1986), CFAC (Ill.) (1977)	EC							
A4	CP	PWC (Qld.) (1997), Merritt (1986), Estonian Railways (2002), AISE (2002), Tradeport (2000) for ports, Drewry Shipping Consultants (1995) for ships	EC							
A5	CP	Szabo (1978), Freebairn and Trace (1988), BIE (1995), Easton (1988)	EC							
A6	CP	Brennan (1990), NEAC (1980), Szabo (1978), Lema (1990), CFAC (Ill.) (1977)	EC							
A7	CP	Lee (1986), Szabo (1978), Lema (1990), CFAC (Ill.) (1977), EPA (U.S.A.) (1994)	EC							
A8	CP	Drewry Shipping Consultants (1995)	EC							

A1.3.2.3 Social Flows

Ref.	Agg.	Source(s)	S. Agg.	R	C	T	G	E	Min.	Max.
A1	WE	BIE (1992) (Road and Rail)	N							
A2		NOHSC (2002)								
A3	See A2									
B1	WE	BIE (1992) (Road and Rail), BTCE (1998) (Ship)	N							
B2	SA	NOHSC (2002), AMSA (2002)	YA							
B3	See B2									

A1.3.3 Generation Subsystem

A1.3.3.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	R	C	T	G	E	Min.	Max.
A1	PW	ECNSW (1991a) and confidential	YA	2	1	3	1	1	4.38^{-2}	8.49^{-2}

A2	PW	DMR (2000), DME (2000)	N	3	2	1	1	1	1.25^{5}	7.55^{5}
A3-A4	PW	Delta Electricity (1999b), Tarong Energy (2000b)	YA	2	2	1	1	1	4.98 5.47	19.9 21.9
A5	PW	Delta Electricity (1999b), ECNSW (1991a), Stanwell (1999), and confidential	YA	2	2	1	1	1	1.83^{2}	4.00^{2}
A6-A15	N	Delta Electricity (1999b), ECNSW (1980)	N	2	2	1	1	1	32.5 22.5 3.75 3.00 0.10 0.15 7.50^{-2} 5.00^{-2} 2.00^{-2} 2.00^{-2}	130 90.0 15.0 12.0 0.40 15.0 7.50 5.00 2.00 2.00
A16	N	Delta Electricity (1999b)	YA	2	1	1	1	1	1.70^{-1}	17.0
A17	FE	Dragun *et al.* (1986)	N	3	2	4	1	1	1.39^{5}	2.60^{5}
A18	PW	Dragun *et al.* (1986), Delta Electricity (1999b), SPCC (1979), ECNSW (1980), BHP Research (1999), Tarong Energy (2000b), Stanwell (1999)	YA	3	2	1	1	1	1.25^{6}	2.34^{6}
A19	See A1			See A1					1.044	1.085
A20	PW	Pacific Power (1999), Delta Electricity (1999b), Tarong Energy (1998), Stanwell (1999)	YA	2	2	1	1	1	5.54^{4}	1.34^{5}
A21	WE	Day (1986), ECNSW (1982)	YA	2	2	1	1	1	1.51^{6}	7.56^{5}
A22	PW	Tarong (2000a), Tarong (2000b), Stanwell (1999)	YA	2	2	1	1	1	1.87^{5}	5.71^{5}

A23	MW	Based on Section A1.4.3.1 A26		5	2	1	4	4	2.73^{-3}	2.73^{-1}
A24	YA	Pacific Power (1999)	N	3	4	1	1	1	3.15^{4}	3.15^{6}
A25-A32	EM	BIC-ST, Diesel, Petrol, Fuel Oil EM	N	2	2	1	1	1	2.73^{5} 2.77 5.12 2.40 8.87^{2} 3.31^{1} 1.12^{3} 1.32^{2}	1.65^{6} 166 30.9 14.5 5.37^{3} 200 6.73^{3} 801
B1	CW	DOE (U.S.A.) (1999), DOE (U.S.A.) (2000f)	N							
B2	SA	See B1 and Leonard *et al.* (2001)	N							
B3 & B6	WE	Leonard *et al.* (2001) and assumptions	N							
B4-B5	See A3-A4									
B7-B17		See B1, Smit and Nieuwlaar (1994), Sierra Pacific Resources (2001), and See A6-A15								
B18	See A16									
B19	See B1									
B20	WE	Calculated from emissions								
B21	See B1									
B22-B23	N	DOE (U.S.A.) (2000f)	N							
B24	WE	DOE (U.S.A.) (1999), Delta Electricity (1999b) and A21	N							
B25	CE	Estimate based on A22	N							

Ref.	Agg.	Source(s)	S. Agg.	R	C	T	G	E	Min.	Max.
B26	MW	DOE (U.S.A.) (2000f) and Section A1.4.3.1 A26	N							
B27	WE	Nautilus Institute (1999) and A24	N							
B28-B35	EM	BIC-IGCC, Diesel, Petrol, NG-CCGT, Coke Breeze EM	N							

A1.3.3.2 Economic Flows

Ref.	Agg.	Source(s)	S.	PM Scores					Range	
			Agg.	R	C	T	G	E	Min.	Max.
A1	CP	NREC (1987), ERDC (1992), NEA (1986), EIA (1996-7), DOE (U.S.A.) (1999), GTZ (1996), DoE (U.K.) (1988), IEA (1992), Stanwell (2002), CSEnergy (2001), Tarong Energy (1999), Intergen (1999), Gallagher and Pierce (1986), IEA (1993), Olds (1973)	EC							
A2	CP	NREC (1987), ERDC (1992), NEA (1994), DOE (U.S.A.) (1999), ECNSW (1991b), GTZ (1996), NEA (1986), NEA (1992), IEA (1992), Sayers and Shields (2001), Simes (2000)	EC							
B1	CP	DoE (U.K.) (1988), DOE (U.S.A.) (1999), DOE (U.S.A.) (2000a-f), IEA (1992), Power Technology (2002), IEA (1993)	EC							
B2	CP	ERDC (1992), DOE (U.S.A.) (1999), DOE (U.S.) (2000a-f), IEA (1992), Maude (1993)	EC							

A1.3.3.3 Social Flows

Ref.	Agg.	Source(s)	S.	PM Scores					Range	
			Agg.	R	C	T	G	E	Min.	Max.
A1	N	Macquarie Generation (2000)	N							
A2	MW	Tarong Energy (2002), Stanwell (2002), Macquarie Generation (2000), CS Energy (2000)	N							
B1	SA	DOE (U.S.A.) (1999) and Section A1.4.3.3 A1	N							

A1.3.4 Transmission Subsystem

A1.3.4.1 Material Flows

Ref.	Agg.	Source(s)	S.	PM Scores					Range	
			Agg.	R	C	T	G	E	Min.	Max.
A1	MC	Macquarie Generation (2000), Pacific Power (2000), Delta Electricity (1999a), Tarong Energy (2000a), Stanwell (2000), CSEnergy (2000), ESAA (1999) for generation, TransGrid (2001), Powerlink (2001) for distances, ESAA (1999) for interstate.	YA	4	5	2	1	1	0.980	0.993

A1.3.4.2 Economic Flows

Ref.	Agg.	Source(s)	S.	PM Scores					Range	
			Agg.	R	C	T	G	E	Min.	Max.
A1	CP	Hirst and Kirby (2001), GPU Powernet (1987), Hydro (Canada) (2001), Kinhill Stearns (1987), Treasury (Qld.) (2001)	EC							

A2	CP	Freeman *et al.* (2002), Powerlink (2002), Electranet (2002a), Electranet (2002b), UMS Group (2000), Simpson (2001)	EC							

A1.3.4.3 Social Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	CW	ElectraNet (2003), SPIPowernet (2003)	N							
A2	MW	Electranet (2003), Transgrid (2003), Fong (2002)	YA							
A3	N	Fong (2002)	YA							

A1.4 BROWN COAL

A1.4.1 Mining Subsystem

A1.4.1.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	PW	Confidential (Multiple)	N	4	2	1	1	1	3.61	5.00
A2	See A7			2	2	1	1	1	2.44^{8}	6.25^{8}
A3- A4	PW	Confidential (Multiple)	N	4	2	1	1	1	1.20^{4} 838	2.30^{5} 1.31^{3}
A5	Estimate from A8			2	2	1	1	1	85	8.53^{3}
A6	PW	Confidential Source	N	3	3	1	1	1	4.26^{7}	1.70^{8}
A7	PW	Yallourn Energy (1999), Hazelwood Power (1999), Loy Yang Power (1999)	YA	2	2	1	1	1	2.44^{8}	6.25^{8}
A8	SA	Hazelwood (1999)	YA	2	2	1	1	1	88	8.81^{3}
A9	PW	Hazelwood Power (1999) and Confidential (Multiple)	N	2	2	1	1	1	1.64^{8}	5.68^{8}
A10-	EM	Diesel, Petrol EM	N	3	5	1	2	3	3.87^{4}	7.24^{5}

A17									1.16 5.87 0.11 54.7 21.3 11.0 2.37	314 3.35^{3} 62 3.12^{4} 1.21^{4} 6.32^{3} 1.31^{3}

A1.4.1.2 Economic Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	CP	VBCC (1982), DITC (1986), SECV (1989)	EC							
A2	CP	VBCC (1982), VAO (1993), Ernst and Whinney (1982)	EC							

A1.4.1.3 Social Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	PW	Confidential (Multiple)	N							

A1.4.2 Transport Subsystem

A1.4.2.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	WE	See A1.3.2.1 A1 for consumption rate, Confidential for distance	N	4	3	5	3	1	0.161	2.57
A2- A4	WE	Based on assumptions	N	5	5	1	1	1	1.00^{9} 495 0.50	1.00^{9} 4.95^{4} 5.00^{3}

A1.4.2.2 Economic Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores					Range	
				R	C	T	G	E	Min.	Max.
A1	CP	VBCC (1982)	EC							
A2	See A1									

A1.4.2.3 Social Flows

No estimates of social flows for brown coal transport.

A1.4.3 Generation Subsystem

A1.4.3.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores					Range	
				R	C	T	G	E	Min.	Max.
A1	WE	Confidential (Multiple)	YA	1	2	1	1	1	5.37^{-2}	0.11
A2	PW	Yallourn Energy (1999), Hazelwood Power (1999), Loy Yang Power (1999)	YA	1	2	1	1	1	1.25^{6}	1.62^{6}
A3- A5	R	SECV (1993) and Confidential (Multiple)	N	2	2	3	1	1	0	641
									0	1.36^{3}
									0	32.9
A6- A8	PW	Confidential (Multiple)	YA	1	1	1	1	1	0	0.90
									4.63	7.06
									0	10.2
A9- A15, A17	N	Confidential	YA	1	2	1	1	1	266	544
									26.5	54.3
									44.2	90.4
									11.0	22.6
									0.47	0.97
									7.90^{-2}	0.16
									0.55	1.13
									0.51	1.04
A16	PW	Confidential (Multiple)	YA	1	2	1	1	1	9.3	26.9
A18	Based on A23			1	2	1	1	1	2.53	5.17

A19	PW	Yallourn Energy (1999), Hazelwood Power (1999), Loy Yang Power (1999), Confidential	YA	1	2	1	1	1	1.90^{6}	3.17^{6}
A20	PW	Confidential (Multiple)	YA	1	2	1	1	1	7.66^{4}	1.17^{5}
A21	Basis 1 GWh + A1			1	2	1	1	1	1.05	1.11
A22	PW	Yallourn Energy (1999), Hazelwood Power (1999), Loy Yang Power (1999)	YA	4	2	1	1	1	1.44^{4}	2.80^{4}
A23	PW	Hazelwood Power (1999), Loy Yang Power (1999)	YA	1	2	1	1	1	2.89	5.90
A24	N	Confidential	YA	1	2	1	1	1	9.11^{5}	1.96^{6}
A25, A27	PW	Yallourn Energy (1999), Loy Yang Power (1999)	YA	1	2	1	1	1	7.67^{5}	1.79^{6}
				1	1	1	1	1	1.10^{5}	1.69^{5}
A26	N	Confidential	YA	1	2	1	1	1	0.00273	0.273
A28- A35	EM	BrC-ST, Fuel Oil, Briquettes, NG-ST, Diesel, Petrol, LPG EM	N	2	2	1	2	1	9.83^{5}	1.37^{6}
				5	2	1	1	1	0.652	60.2
				3	5	1	2	3	2.06	204
				2	2	1	1	1	1.61	168
				3	5	1	2	3	153	1.59^{4}
									21.3	2.09^{3}
									182	1.80^{4}
									44.6	4.68^{3}
B1	WE	Based on Section A1.3.3.1 B1 plus penalty for MTE drier.	N							
B2	WE	Assumption backed by simulation	N							
B3	WE	Based on Section A1.3.3.1 B3	N							
B4- B5	MW	Based on A6-A8	N							
B6-	R	Based on Section A1.3.3.1	N							

B15		B8-B17, some ratios based on differences in fuel qualities (i.e. S contents).								
B16	N	Based on Section A1.3.3.1 B18	N							
B17	C	Calculated from other water flows.	N							
B18	R	Based on Section A1.3.3.1 B19 and simulation	N							
B20	C	Based on coal composition.	N							
B19	Basis 1 GWh + B1									
B22	See B16									
B23	R	Based on A24	N							
B24	WE	Based on requirements and MTE drier wastewater (Confidential)	N							
B25	MW	A26	N							
B26	PW	Based on Section A1.3.3.1 B27	N							
B27-B34	EM	BrC-IGCC, NG-CCGT, Diesel, Petrol EM	N							

A1.4.3.2 Economic Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	CP	NREC (1987), ERDC (1992), SECV (1989)	EC							
A2	CP	Ernst and Whinney (1982), ERDC (1992), Loy Yang Power (1999), SKM (1997)	EC							
B1	CP	Section A1.3.3.2 B1, Confidential for MTE costs	EC							
B2	R	Based on Section A1.3.3.2 B2	EC							

A1.4.3.3 Social Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	PW	Confidential (Multiple)	YA							
A2	MW	Confidential (Multiple)	YA							
B1	CW	DOE (U.S.A.) (1999) and DOE (U.S.A.) (2000f)	YA							
B2	Based on A2									

A1.4.4 Transmission Subsystem

A1.4.4.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	MC	Yallourn Energy (1999), Hazelwood Power (1999), Loy Yang Power (1999) for generation, ESAA (1999) for interstate.	YA	4	5	2	1	1	0.961	0.993

A1.4.4.2 Economic Flows

See Section A1.3.4.2.

A1.4.4.3 Social Flows

See Section A1.3.4.3.

A1.5 Natural Gas and Liquefied Natural Gas

A1.5.1 Mining Subsystem

A1.5.1.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1,	YA	Basis + APPEA (1999)	N							

A5										
A2-A4	YA	APPEA (1999)	N							
A6	N	MMS (1998)	N							
A7	PW	EPS (Canada) (1989), Canada-Newfoundland Offshore Petroleum Board (2001)	N							
A9	PW	EPA (U.S.A.) (1999), DTI (U.K.) (2000), Confidential	N							
A10-A11	See A6									
A12, A14	N	EPS (Canada) (1989)	N							
A13	PW	UKOOA (1999), DTI (2000)	YA							
A16	PW	Scott *et al.* (1997), Dedman (2000), Santos (1999b), Sampson (2000)	N							
A17-A19	EM	NG-F, Diesel, Petrol, Aviation Fuel, Crude Oil EM* for combustion, APPEA (1999) for fugitive	N							
A20-A24	EM	NG-F, Diesel, Petrol, Aviation Fuel, Crude Oil EM*	N							
A25	YA	APPEA (1999)	YA							

A1.5.1.2 Economic Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	CP and FA	ACIL (1998), OMV (2001), Santos (1999a), Woodside Offshore Petroleum (1992), Woodside (2000), BHPBilliton (2001b), Anonymous (2002c), APPEA (2001a), Mobil Australia (1999), OTD (N.T.) (2001) for offshore production, FA for onshore production	EC							
A2	CP	ExxonMobil (2002), BHPBilliton (2001b), Santos (1999a), Woodside (2000), UKOOA (2001) for production	EC							
B1	CP	YPC (2001), Hydrocarbon Processing (2001,1999), DoE (U.K.) (1980), Special Correspondent (1977), Mallet (1987), Anonymous (2002c, 1997), Santos (1999a) for processing	EC							
B2	CP	Zauner (2000), DoE (U.K.) (1980), AGA (2001) for processing	EC							

* Special EM for NG mining (see Section A1.8)

A1.5.1.3 Social Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	PW	Woodside (2000) offshore, Santos (1999b) onshore	YA							
A2-A3	MW	NOHSC (2002), APPEA (2001b)	N							
B1	PW	Woodside (2000)	YA							
B2-B3	See A2-A3									

A1.5.2 Transport Subsystem

A1.5.2.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1-A4	YA	AGA (1997)	N							
A17	See A1-A4									
A18	EM	NG-OCGT, Diesel, Petrol, LPG EM for combustion, AGA (1997) for fugitive and other	N							
A19-A20	EM	NG-OCGT, Diesel, Petrol, LPG EM, AGA (1997) for fugitive	N							
A21-A25	EM	NG-OCGT, Diesel, Petrol, LPG EM	N							
A26	YA	AGA (1997)	N							
B1	PW	Tamura *et al.* (2001), Snam (2001), Snam (1999) for vaporisation, A1 for pieline	N							
B2	N	Tamura *et al.* (2001)	N							
B3-B5	See A2-A4									
B6	N	Snam (1999)	N							
B10	WE	Tamura *et al.* (2001) for ocean transport, Snam (2001), Snam (1999), Tamura *et al.* (2001) for vaporisation, A2 for pipeline	N							
B11	N	Snam (1999)	N							
B12	See B6									
B13-	EM	NG-OCGT and Water, Fuel	N							

B15		Oil (Water) Diesel, Petrol, LPG EM for combustion, Snam (1999) and AGA (1997) for fugitive								
B13-B21	EM	Natural Gas (Water, OCGT), Fuel Oil (Water) Diesel, Petrol, LPG EM	N							

A1.5.2.2 Economic Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	CP	Origin Energy (2002), McDonald (2001), Duke Energy (2000a, 2000b), Epic Energy (2001), YPC (2001), Anonymous (1998a, 1998b), Klaassen *et al.* (1999)	EC							
A2	WE and CP	HEE (2002b), Cedigaz (2000), OTD (N.T.) (2001), YPC (2001), BG Group (2002), Hydrocarbon Processing (2001, 1999), TotalFinaElf (2000) for LNG plants. Flower (1998), TotalFinaElf (2000), Klaassen, *et al.* (1999) for ocean transport Anonymous (2002b), Cedigaz (2000), Bradner (2002), Hydrocarbon Processing (2001), Rigzone (2003), TotalFinaElf (2000) for vapourisation plant. Supporting information:	EC							

		TotalFinaElf (2000), EnerSea Transport (2002), Golar LNG (2001), OTA (U.S.A.) (1980)								
B1	CP	Systek (2002), ADB (2002), HEE (2002b), NiSource (2001), GPU GasNet (2002), Freeman *et al.* (2002)	EC							
B2	CP	HEE (2002a), BG Group (2003), EIA (2002, 1997), OTA (U.S.A.) (1980), Enoch and Frey (2002), Martin (2001)	EC							

A1.5.2.3 Social Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	PW	Epic Energy (2003)	N							
A2-A3	SA	DOL (U.S.A.) (1996), DFFP (U.S.A.) (1997)	YA							
B1	WE	Golar LNG Ltd. (2002) for administration, Eddy (1998) for crewing	N							
B2-B3	YA	AMSA (2002)	N							

A1.5.3 Generation Subsystem

A1.5.3.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	PW	NERC (2000), Confidential	N							
A2	PW	ETSA Corporation (1997), Office of Atmospheric	YA							

		Programs (EPA) (2001)								
A3-A5	MW	Based on Section A1.4.3.1 A6-A8	N							
A6-A12	PW	SECV (1973) and Sections A1.3.3.1 and A1.4.3.1	N							
A13	See A21									
A14	PW	SECV (1973), Generation Victoria (1997), Optima Energy (2000)	N							
A15	PW	SECV (1973), Generation Victoria (1997)	N							
A20-A21	N	SECV (1973)	N							
A22	See Section A1.3.3.1									
A23	N	Generation Victoria (1997) and mass balance	N							
A24	MW	Based on Section A1.4.3.1 A26	N							
A25-A32	EM	NG-ST, Diesel, Petrol, LPG EM	N							
B1	PW	ECNSW (1991b), NERC (2000)	YA							
B2	PW	Alstom (2001), SECV (1993)	N							
B3	YA	SECV (1993)	N							
B4-B6	See A3-A5									
B7-B8	PW	Based on A6-A12 with reduced water requirements	N							
B9	N	SPIA (2001)	N							
B10	PW	Pavri and Moore (2001), Davis and Black (2000), NYPA (2001)	N							
B12	See B9									

B13	N	NYPA (1990)	N							
B14	MW	Based on Section A1.4.3.1 A26	N							
B15-B22	EM	NG-OCGT, Fuel Oil-OCGT, Diesel, Petrol, LPG EM	N							
C1	PW	NYPA (2001), NERC (2000)	YA							
C2	SA	NYPA (2001), Alstom (2001), DIT (2000)	N							
C3	PW	See B3	N							
C4-C6	See A3-A5									
C7-C13	WE	Based on A6-A12 with modified water requirements	N							
C14	WE	Based on A13 and B9	N							
C15	WE	Clark Public Utilities (2001), BHP Minerals Technology (2001), NYPA (2001)	N							
C16	N	NYPA (2001)	N							
C18	SA	NYPA (2001), SECV (1973)	N							
C19	See C14									
C20	See Section A1.3.3.1									
C21	WE	Based on other flows	N							
C22	MW	Based on Section A1.4.3.1 A26	N							
C23-C30	EM	NG-CCGT, Fuel Oil-CCGT, Diesel, Petrol, LPG EM	N							

A1.5.3.2 Economic Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1	CP	GTZ (1996), Johnson (1987), Olds (1973), NEA (1998, 1992), SECV (1987)	EC							
A2	CP	GTZ (1996), NEA (1992, 1998), Frechill, Hollingdale and Page (1999), SECV (1987)	EC							
B1	CP	ERDC (1992), GTZ (1996), BGAG (2002), Johnson (1987), Anonymous (2002a), SECV (1987), Driver and Ritchey (1998)	EC							
B2	CP	ERDC (1992), GTZ (1996), SECV (1987), Driver and Ritchey (1998)	EC							
C1	CP	DOE (U.S.A.) (1999), National Power (2000), ERDC (1992), GTZ (1996), Treasury (Qld.) (2000), ECNSW (1991b), SCPPA (2002), SECV (1987), Driver and Ritchey (1998)	EC							
C2	CP	ERDC (1992), DOE (U.S.A.) (1999), ECNSW (1991), SCPPA (2002), IEA (1992), GTZ (1996), NEA (1998), SECV (1987), Driver and Ritchey (1998)	EC							

A1.5.3.3 Social Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores R	C	T	G	E	Range Min.	Max.
A1, B1	MW	Ecogen Energy (1999)	N							
C1	R	DOE (U.S.A.) (1999) and Section A1.3.3.3 A1	N							
A2, B2, C2	EN	Ecogen Energy (1999)	N							

A1.5.4 Transmission Subsystem

A1.5.4.1 Material Flows

Ref.	Agg.	Source(s)	S. Agg.	PM Scores					Range	
				R	C	T	G	E	Min.	Max.
A1	See Section A1.3.4.1 A1									

A1.5.4.2 Economic Flows

See Section A1.3.4.2.

A1.5.4.3 Social Flows

See Section A1.3.4.3.

A1.6 CONVERSIONS NECESSARY TO PRODUCE INDICATORS FROM COLLECTED DATA

A1.6.1 Environmental Factors

Ref.	Agg.	Source(s)	S. Agg.	PM Scores					Range	
				R	C	T	G	E	Min.	Max.
A1	MC	AGA (2000a) for gas consumption, APPEA (1998) for production	N							
B1	Eq. 3.2.1	ABS (1998c)	YA							
C1-C4	Eq. 3.2.4	ABS (2000), ABS (1998b), ABS (1998c)	YA							
C5	Eq. 3.2.4	ABS (2000), NGGIC (2000)	YA							
C6	Eq. 3.2.4	NGGIC (2000), NPI (2001)	YA							
C7	Eq. 3.2.4	NGGIC (2000)	YA							
C8	Eq. 3.2.4	NPI (2001), NGGIC (2000)	YA							
C9	Eq. 3.2.4	ABS (1998a)	YA							

A1.6.2 Economic Factors

Ref.	Agg.	Source(s)	S. Agg.	PM Scores					Range	
				R	C	T	G	E	Min.	Max.
A1	PW	DMR (2000), Alyward and Sutherland (2000), DME (1998) and DME (2000)	YA							
A2	N	Freebairn and Trace (1998)	N							
A3, A9, A12	N	SECV (1989)	N							
A4	N	Assumption (economics based on entire field estimate, no Australian field has stopped production)	N							
A5	N	CFAC (Ill.) (1977)	N							
A6	N	Spath *et al.* (1999)	N							
A7	N	Freebairn and Trace (1998)	N							
A8	N	Chrzanowski (1985)	N							
A10	N	Pipelines are long-life projects (40-50 years)	N							
A11	N	Flower (1998)	N							
A13	N	Richards (1998), DOE (U.S.A.) (1999), SKM (1997)	N							
A14-A15, A22	YA	Simes (2000)	EC							

A16-A17, A19-A21, A24-A25	N	O & M of proceeding subsystem.	EC							
A18, A26, A28, A30	YA	Zauner (2000)	EC							
A23, A27	YA	Institute of Energy Economics (Japan) (2002)	EC							
A29, A31	YA	IEA (1999)	EC							
A32	N	ACCC (1986)	N							
A33	SA	ACCC (1986), Errington and Kirby (1993)	N							
A34, A39, A44	N	Ernst and Whinney (1982)	N							
A35-A36	SA	EIA (2002), Brennan *et al.* (1980)	N							
A37	N	Freebairn and Trace (1988)	N							
A38	N	BTCE (1998)	N							
A40	N	DoE (U.K.) (1980)	N							
A41	SA	DoE (U.K.) (1980), Bourgeois (1990), OTA (1980)	N							
A42, A43	N	DOE (U.S.A.) (1999)	N							
A45	N	DOE (DOE) (U.S.A.) (2000f)	N							

A46	N	Frechill, Hollingdale and Page (1999)	N							
A47	N	ERDC (1992)	N							
A48	N	IEA (1992)	N							
A49	N	National Grid (2001)	N							
B1	N	ABS (2003b)	YA							
B2	N	ABS (2003c)	YA							
B3	N	ABS (2003a)	YA							
B4	N	ABS (2003a), ABS (2003b)	YA							

A1.6.3 Social Factors

Ref.	Agg.	Source(s)	S. Agg.	PM Scores					Range	
				R	C	T	G	E	Min.	Max.
B1	N	ABS (2003d)	RA							
B2-B3	N	NOHSC (2002)	YA							

A1.7 Application of Uncertainty and Sensitivity Analyses

Ref.	Agg.	Source(s)	S. Agg.	PM Scores					Range	
				R	C	T	G	E	Min.	Max.
B1-B4	MC	Simes (2000)	YA							
B5-B10	MC	APPEA (1999), ABS (2001)	YA							

A1.8 Emission Factors

Estimation of most gaseous and some particulate (non-dust) emissions was by emission factors (EM). Section A1.10.3 contains an example of emission factor use.

Fuel	Type	Substance	Source(s)	Value (kg per kg)
BIC	ST	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2	NGGIC (1998a)	2.19, 2.16 $^{-5}$, 4.08 $^{-5}$, 1.92 $^{-5}$, 7.11 $^{-3}$, 2.64 $^{-4}$, 8.88 $^{-3}$

BIC	ST	PM	Pacific Power (2000), Delta Electricity (1999b), Tarong Energy (2000a), NPI (1999)	1.06^{-3}
	IGCC	CO_2, CH_4, NO_x, CO, SO_2, PM VOC N_2O	DOE (U.S.A.) (1999), Leonard *et al.* (2001) Smit and Nieuwlaar (1994), DOE (U.S.A.) (1997), Sierra Pacific Resources (2001), IEA (1993), IEA (1992), Keeler (2001)	$2.43, 1.16^{-4}, 5.13^{-4}$, $5.83^{-4}, 1.98^{-4}, 2.33^{-5}$ $7.58^{-7}, 3.48^{-5}$
BrC	ST	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2 PM	NGGIC (1998a) Yallourn (1999), Hazelwood Power (1999), Loy Yang (2000)	$0.824, 4.32^{-6}, 1.47^{-5}$, $1.21^{-5}, 1.14^{-3}$, $1.50^{-4}, 1.29^{-3}$ 3.36^{-4}
	IGCC	CO_2, CH_4, VOC, N_2O, NO_x, CO, O_2, PM	Based on BIC-IGCC and BrC-ST	$0.950, 4.18^{-4}, 2.73^{-6}$, $1.30^{-5}, 1.92^{-4}$, $2.70^{-4}, 2.55^{-3}, 2.61^{-5}$

NG	ST	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2 PM	NGGIC (1998a) NPI (1999)	$2.62, 5.12^{-6}, 3.29^{-5}$, $5.12^{-6}, 5.95^{-3}$, $8.20^{-4}, 1.18^{-7}$ 6.65^{-3}
	OCGT	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2 PM	NGGIC (1998a) NPI (1999)	$2.63, 3.48^{-4}, 8.06^{-3}$, $5.12^{-6}, 8.38^{-3}$, $1.94^{-3}, 1.18^{-7}$ 9.21^{-4}
	CCGT	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2, PM	Argonne National Laboratory (1996)	$2.71, 1.13^{-4}, 6.34^{-5}$, $4.98^{-5}, 3.54^{-3}$, $1.67^{-4}, 1.40^{-5}, 1.63^{-4}$

Fuel Oil	ST	CO_2, CH_4, VOC, N_2O NO_x, CO, SO_2, PM	NGGIC (1998a) NPI (1999)	$2.98, 4.29^{-3}, 3.43^{-5}$, 2.57^{-5} $8.40^{-3}, 6.30^{-4}$, $5.95^{-2}, 3.28^{-4}$
	Ship (W)	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2, PM	Based on Fuel Oil-ST and BIC-ST	$2.98, 2.51^{-3}, 2.23^{-2}$, $2.05^{-4}, 5.49^{-2}$, $7.44^{-4}, 5.95^{-2}, 3.28^{-4}$
Fuel Oil-IGCC (see Fuel Oil-ST)				
Fuel Oil-OCGT (see Fuel Oil-ST)				
Fuel Oil-CCGT (see Fuel Oil-ST)				
Coke Breeze (see BIC-ST)				
Briquettes	ST	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2, PM	Based on BrC-ST, NGGIC (1998a) and DISR (1999)	$1.71, 8.98^{-6}, 3.05^{-5}$, $2.51^{-5}, 2.37^{-3}$, $3.11^{-4}, 2.69^{-3}, 6.99^{-4}$
Diesel	Automotive	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2 PM	NGGIC (1998a), NGGIC (1998c) NGGIC (1998b)	$3.13, 2.56^{-4}, 4.85^{-3}$, $8.98^{-5}, 4.51^{-2}$, $1.75^{-2}, 9.16^{-3}$ 1.86^{-3}
	Ship (W)	CO_2, CH_4, VOC, N_2O, NO_x, CO SO_2, PM	APPEA (1999) See Diesel Automotive	$3.2, 2.70^{-4}, 2.40^{-3}$ $2.20^{-4}, 5.90^{-2}, 8.00^{-3}$ $9.16^{-3}, 1.86^{-3}$
Petrol	Automotive	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2 PM	NGGIC (1998a), NGGIC (1998c) NGGIC (1998b)	$3.06, 1.21^{-2}, 9.28^{-4}$, $4.64^{-5}, 8.82^{-3}$, $5.10^{-3}, 6.96^{-4}$ 2.01^{-3}
LPG	Automotive	CO_2, CH_4, VOC, N_2O, NO_x, CO, SO_2 PM	NGGIC (1998a), NGGIC (1998c) Wang and Huang (1999)	$2.95, 1.09^{-3}, 2.03^{-2}$, $4.96^{-5}, 2.17^{-2}$, $0.271, 3.97^{-4}$ 3.28^{-3}

Natural Gas mining subsystem emission factors (APPEA (1999) for CO_2 to CO, SO_2 and PM based on NG-ST, Fuel Oil-ST (for crude oil), diesel (automotive), and petrol (automotive) for aviation fuel).

Subst-ance	NG-F	Crude Oil	Diesel (turbines)	Diesel (engines)	NG (turbines)	NG (engines)	Aviation Fuel
CO_2	2.75	3.2	3.2	3.2	2.75	2.75	3.2
CH_4	3.50^{-2}	3.30^{-4}	8.00^{-5}	1.40^{-4}	4.20^{-4}	2.80^{-2}	8.70^{-5}
VOC	1.50^{-2}	2.97^{-3}	7.00^{-4}	1.90^{-3}	5.10^{-5}	3.00^{-3}	8.00^{-4}
N_2O	8.10^{-5}	2.20^{-4}	2.20^{-4}	2.20^{-4}	2.20^{-4}	2.20^{-4}	2.20^{-4}
NO_x	1.50^{-3}	3.70^{-3}	9.40^{-3}	7.00^{-2}	6.70^{-3}	7.60^{-2}	1.25^{-2}
CO	8.70^{-3}	1.80^{-2}	2.10^{-3}	1.90^{-2}	2.70^{-3}	9.60^{-3}	5.20^{-3}
SO_2	1.18^{-7}	5.95^{-2}	9.16^{-3}	9.16^{-3}	1.18^{-7}	1.18^{-7}	6.96^{-4}
PM	9.21^{-4}	3.28^{-4}	1.86^{-3}	1.86^{-3}	9.21^{-4}	9.21^{-4}	2.01^{-3}

A1.9 AUSTRALIAN NORMALISATION DATA FOR THE ENVIRONMENTAL INDICATORS

This section shows the base data used to generate the Australian normalisation factors, shown in Table 4.3.49 (Chapter 4), for the environmental indicators.

Table of the data used to produce normalisation factors for the CC, EU, AD, PS and SW indicators (see Section 4.3.6.2 for sources).

Substance	Mt per annum	Substance	Mt per annum
CO2	312.1	PFCs	0.0002
CH4	5.5	SF6	0
N2O	0.089	SO2	1.8
NOx	2.6	Ammonia	0.016
CO	18.6	Solid Waste	2.12205×10^4
NMVOC	1.9		

Table of the data used to produce normalisation factors for the RD W and RD A indicators (see Section 4.3.6.2 for sources).

Substance	Production (Mt)	Reserve (Mt)	Substance	Production (Mt)	Reserve (Mt)
antimony (Sb)	1.3	89.9	uranium (U)	5	622
cadmium (Cd)	1.9	132	zinc (Zn)	1.1	3.99×10^4
cobalt (Co)	0.9	414	bauxite	43.1	3.02×10^6
copper (Cu)	0.5	2.37×10^4	iron (ore)	147	1.78×10^7
gold (Au)	289	4.45	manganese (ore)	2.1	1.18×10^5
lead (Pb)	513	1.87×10^4	Black Coal	2.52×10^5	1.72×10^8
lithium (Li)	3	166	Brown Coal	5.30×10^4	1.44×10^8

Substance	Production (Mt)	Reserve (Mt)	Substance	Production (Mt)	Reserve (Mt)
nickel (Ni)	113	6370	Natural Gas	2.36×10^4	2.55×10^6
silver (Ag)	1	43.3	Oil	2.07×10^4	4.86×10^5
tantalum (Ta)	0.3	8.1	Condensate	2850	1.97×10^5
tin (Sn)	12.2	120	LPG	2590	1.99×10^5
tungsten (W); wolfraam	0.1	0.9			

A1.10 AGGREGATION PROCEDURES

A1.10.1 Overview of Aggregation Procedures

In this section are details of the methods used to produce aggregated data from multiple sources. Sections A1.3 to A1.8 provide details on the data sources and the methods applied in each case.

A1.10.2 Averages (YA, FA, SA, RA, PW, CW and MW)

A1.10.2.1 SA (simple average), YA (yearly average) and RA (rolling average)

A simple average is an average of multiple values. A yearly average is an average of values from multiple years. For example: NG consumption in Generation subsystem (Data Ref. A2).

Year	kg per GWhpa
1994-95	196044
1995-96	199759

Thus:

$$V_{YA} = \sum_{y=1}^{2} V_y \Big/ 2 = \frac{196044 + 199759}{2} = 197901.5 \text{ kg per GWhpa}$$

A rolling average (RA) is a yearly average over **consecutive** years (i.e. 1995-1997 is a 3-year rolling average).

A1.10.2.2 FA (factored average)

A factored average is an aggregate produced using averages (V_1 and V_2), where the aggregate is not a simple sum ($V_A \neq V_1 + V_2$). In this case, factors (F_1 and F_2) enable summation. For example: Diesel consumption in BlC mining subsystem (Data Ref. C3). Underground and surface mining consume different amounts of diesel. The proportion of average BlC produced in underground and surface mines respectively is not 50 %.

Mine Type	Diesel (kg per Mtpa)	% of coal
Surface	21730	24.7
Underground	1625023	75.3

Thus:

$$V_A = F_1.V_1 + F_2.V_2 = (21730 \, x \, 24.7) + (1625023 \, x \, 75.3) = 1646752 \text{ kg per Mtpa}$$

A1.10.2.3 PW (production), CW (capacity) and MW (employment or employee hours-weighted averages)

Production-weighted averages (V_{PW}) assume that systems that produce (P) more of the desired product are more accurate estimates (V_i) than those that produce less. For example: BIC, ST generation subsystem, coal consumption.

Power Station	Coal (kg per GWhpa)	Generation (GWhpa)
Bayswater	483589	15364
Eraring	755259	7400

Thus:

$$V_{PW} = \sum_{i=1}^{T}(V_i.P_i) \Big/ \sum_{i=1}^{T} P_i = \frac{(V_1.P_1 + V_2.P_2)}{(P_1 + P_2)} = \frac{(483589 \, x \, 15364 + 755259 \, x \, 7400)}{(15364 + 7400)}$$

$$= 571902 \text{ kg per GWhpa}$$

Similarly, capacity-weighted averages (V_{CW}) assume that systems that have greater capacity (C) to produce the desired product are more accurate estimates (V_i) than those that have less capacity.

$$V_{CW} = \sum_{i=1}^{T}(V_i.C_i) \Big/ \sum_{i=1}^{T} C_i$$

Employment-weighted averages (V_{EW}) assume that systems that have greater employment (E) are more accurate estimates (V_i) than those that have less employment, for social flows.

$$V_{EW} = \sum_{i=1}^{T}(V_i.E_i) \Big/ \sum_{i=1}^{T} E_i$$

For other flows, an employment-weighted average (V_{EW}) is a value produced by weighting another systems value (V_{OS}) by the relative employment in each system (E_{EW} and E_{OS}). For example: BIC, IGCC generation subsystem, sewerage emissions.

Fuel	Technology	Employment (per GWh)	Sewerage (kg per GWh)
BrC	ST	0.0231	0.0273
BIC	IGCC	0.0281	$V_{BIC\text{-}IGCC}$

Thus,

$$V_{BIC\text{-}IGCC} = V_{BrC\text{-}ST}\left(E_{BIC\text{-}IGCC}/E_{BrC\text{-}ST}\right) = 0.0273(0.0281/0.0231) = 0.0218 \text{ kg per GWh}$$

A1.10.3 Emission factors (EM)

Emission factors (EM) assume consistent fuel compositions. The estimation of the emission of each substance (E_i) uses the consumption rate of a fuel (m_F) and the appropriate emission factor for the fuel and substance ($EM_{F,i}$). For example: BIC mining subsystem, CO_2 and methane emissions. Diesel and petrol rates are from Section 4.3.2.1.2. The EM are from Section A1.7.

Substance	Rate (kg per Mtpa)	EM_{CO2} (kg per kg)	EM_{CH4} (kg per kg)
Diesel	1.50×10^6	3.13	2.56×10^{-4}
Petrol	1140	3.06	1.21×10^{-2}

Thus:

$$E_{CO2} = m_D \, x \, EM_{D,CO2} + m_P \, x \, EM_{P,CO2} = 1.50 \times 10^6 \, x \, 3.13 + 1140 \, x \, 3.06$$
$$= 4.70 \times 10^6 \text{ kg per Mtpa}$$

$$E_{CH4} = m_D \, x \, EM_{D,CH4} + m_P \, x \, EM_{P,CH4} = 1.50 \times 10^6 \, x \, 2.56 \times 10^{-2} + 1140 \, x \, 1.21 \times 10^{-2}$$
$$= 3.84 \times 10^4 \text{ kg per Mtpa}$$

A1.10.4 Economic Correlations (CP and EC)

A1.10.4.1 CP (correlation using power function)

Economic source data aggregation uses a power-law correlation (see Equations 3.3.6 and 3.3.10). This correlation uses a computer program (CurveExpert 1.3©), which also provides estimates of error and other details. For example: BIC, ST generation subsystem, capital cost (Data Ref. A1).

$$I = 13.6(Q)^{0.663}$$

Equation 4.3.20

for: Q = 50 to 2800 MW and I = $ 168 to 2410 million (AUD 2000).

Other details: standard error (s^2) = 327; correlation coefficient (R) = 0.85; number of data points = 61 (3 excluded outliers); and references = 15. These other details are available on request.

A1.10.4.2 EC (economic correlation)

Economic correlation converts economic values (EV) of non-basis currency and age into the appropriate basis (AUD 2000). Two steps are necessary. The first step is to convert the original source currency into AUD using market currency conversion factors (MCF). MCF are available from many sources, including http://pacific.commerce.ubc.ca/xr/ and www.fxtop.com. The second step uses historic consumer price indexes (CPI) to change the age of the estimate. Short-term CPI are available from ABS (2002a), and long term from ABS (2002b).

$$EV_{(AUD\,2000)} = EV_{(X\,Y)}.MCF_{\left(\frac{AUD}{X},Y\right)}.\frac{CPI_{2000}}{CPI_Y}$$

where: $EV_{(AUD\,2000)}$ is the converted estimate; $EV_{(X\,Y)}$ is the original estimate in currency X and with basis (or published) year Y; $MCF_{(AUD/X,Y)}$ is the market currency factor for converting X currency to AUD currency in year Y; and CPI_{2000} and CPI_Y are the consumer price indexes for Australia in the years Y and 2000.

For example: BIC, ST generation subsystem, capital cost. DOE (U.S.A.) (1999) estimate for ST system (397.5 MW) is \$ 446859 (USD 1998) (January). $MCF_{(AUD/USD,1998)}$ = 1.523 AUD per USD in 1998. CPI_{2000} and CPI_{1998} = 131.3 and 120.3 (ABS (2002a)).

Thus:

$$EV_{(AUD\,2000)} = EV_{(USD1998)}.MCF_{\left(\frac{AUD}{USD},1998\right)}.\frac{CPI_{2000}}{CPI_{1998}} = (446859)(1.523)\left(\frac{131.3}{120.3}\right)$$
$$= \$\,742796\,(AUD\,2000)$$

A1.10.5 Other Types (FE, WE, MC and R)

A1.10.5.1 FE (estimate obtained by applying a factor to another data value)

Only one FE estimate appears in the data set, high quality water consumption (m_{HQW}) in the BIC generation subsystem. This value is the product of the low quality water consumption (m_{LQW} = 1.78 x 10^6) and a factor (f = 10 % of $m_{LQW+HQW}$).

$$m_{HQW} = m_{LQW}.f/(1-f) = (1.78 \times 10^6)(0.1/(1-0.1)) = 1.98 \times 10^5 \text{ kg per GWh}$$

A1.10.5.2 WE (calculation built in parts using separate sources for each part)

A worked estimate (V_{WE}) uses multiple sources to determine parts of the estimate (V_i), and then sums them using factors (F_i). FA is a special case of WE, in which the various V_i values are averages. For example: see Section A1.10.2.2.

$$V_{PW} = \sum_{i=1}^{T}(V_i.F_i)$$

A1.10.5.3 MC (solution of multiple linear, multivariate equations)

Some reported data (V) is for multiple products (i.e. A + B + C). Thus: V = $V_A + V_B + V_C$. It is difficult to establish the contribution of one particular product (i.e. V_A) from this reported data. However, if a number of different sources (1, 2 and 3) report V, then:

$$V_1 = V_{A,1} + V_{B,1} + V_{C,1}$$
$$V_2 = V_{A,2} + V_{B,2} + V_{C,2}$$
$$V_3 = V_{A,3} + V_{B,3} + V_{C,3}$$

If the proportional contributions of each product can be assumed identical for each source (i.e. the same amount of V is caused for the same amount of A produced), then:

$$V_1 = V_{A,1} + V_{B,1} + V_{C,1} = P_A.V_1 + P_B.V_1 + P_C.V_1$$
$$V_2 = V_{A,2} + V_{B,2} + V_{C,2} = P_A.V_2 + P_B.V_2 + P_C.V_2$$
$$V_3 = V_{A,3} + V_{B,3} + V_{C,3} = P_A.V_3 + P_B.V_3 + P_C.V_3$$

Solving this set of equations uses matrix methods:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} P_A.V_1 + P_B.V_1 + P_C.V_1 \\ P_A.V_2 + P_B.V_2 + P_C.V_2 \\ P_A.V_3 + P_B.V_3 + P_C.V_3 \end{bmatrix} = \begin{bmatrix} V_1 & V_1 & V_1 \\ V_2 & V_2 & V_2 \\ V_3 & V_3 & V_3 \end{bmatrix} x \begin{bmatrix} P_A \\ P_B \\ P_C \end{bmatrix}$$

or

$$\begin{bmatrix} P_A \\ P_B \\ P_C \end{bmatrix} = \begin{bmatrix} V_1 & V_1 & V_1 \\ V_2 & V_2 & V_2 \\ V_3 & V_3 & V_3 \end{bmatrix}^{-1} x \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

For example: Environmental conversion factors, NG mining subsystem, fuel gas consumption (Data Ref. A1).

State	Production (kt)					Fuel Gas (kt)
	NG	LPG	LNG	Condensate	Crude	
Victoria	3846	1159	0	576	10622	664
Queensland	994	125	0	142	626	70
WA	4284	528	7397	4704	9031	1477
SA	3722	411	0	380	569	215
NT	355	0	0	0	961	4
Australia	13201	2223	7397	5802	21809	2431

Thus:

$$\begin{bmatrix} 664 \\ 70 \\ 1477 \\ 215 \\ 4 \\ 2431 \end{bmatrix} = \begin{bmatrix} 3846.P_{NG} + 1159.P_{LPG} + 576.P_{Cond.} + 10622.P_{Oil} \\ 994.P_{NG} + 125.P_{LPG} + 142.P_{Cond.} + 626.P_{Oil} \\ 4284.P_{NG} + 528.P_{LPG} + 7397.P_{LNG} + 4704.P_{Cond.} + 9031.P_{Oil} \\ 3722.P_{NG} + 411.P_{LPG} + 380.P_{Cond.} + 569.P_{Oil} \\ 355.P_{NG} + 961.P_{Oil} \\ 13201.P_{NG} + 2223.P_{LPG} + 7397.P_{LNG} + 5802.P_{Cond.} + 21809.P_{Oil} \end{bmatrix}$$

or

$$\begin{bmatrix} 664 \\ 70 \\ 1477 \\ 215 \\ 4 \\ 2431 \end{bmatrix} = \begin{bmatrix} 3846.P_{NG} + 12358.P_{Liquid} \\ 994.P_{NG} + 892.P_{Liquid} \\ 4284.P_{NG} + 7397.P_{LNG} + 14263.P_{Liquid} \\ 3722.P_{NG} + 1360.P_{Liquid} \\ 355.P_{NG} + 961.P_{Liquid} \\ 13201.P_{NG} + 7397.P_{LNG} + 21809.P_{Liquid} \end{bmatrix}$$

Using a number of sets of three equations from the second form (i.e. below) enables the estimation of the fuel gas consumption for each type of fuel: P_{NG} = 0.0410 kg fuel gas per kg natural gas, P_{LNG} = 0.106 kg fuel gas per kg LNG, and P_{Liquid} = 0.0363 kg fuel gas per kg liquids (LPG, crude oil and condensate).

Example set:

$$\begin{bmatrix} 70 \\ 1477 \\ 215 \end{bmatrix} = \begin{bmatrix} 994.P_{NG} + 892.P_{Liquid} \\ 4284.P_{NG} + 7397.P_{LNG} + 14263.P_{Liquid} \\ 3722.P_{NG} + 1360.P_{Liquid} \end{bmatrix}$$

or

$$\begin{bmatrix} P_{NG} \\ P_{LNG} \\ P_{Liquid} \end{bmatrix} = \begin{bmatrix} 70 \\ 1477 \\ 215 \end{bmatrix} \begin{bmatrix} 994 & 0 & 892 \\ 4284 & 7397 & 14263 \\ 3722 & 0 & 1360 \end{bmatrix}^{-1} = \begin{bmatrix} 0.0488 \\ 0.124 \\ 0.0245 \end{bmatrix}$$

Thus P_{NG} = 0.0488 kg fuel gas per kg natural gas, P_{LNG} = 0.124 kg fuel gas per kg

LNG, and P_{Liquid} = 0.0245 kg fuel gas per kg liquids (LPG, crude oil and condensate).

A1.10.5.4 R (estimate relying on ratios based on old data);

Ratio based estimates (V_R) use ratios from one source, with data from another, to produce an estimate. There is one such case: BrC, ST generation, auxiliary fuel consumption. The auxiliary fuel requirements were similar for each of three included power stations, in both an old public source (F_O = 0.11 GWh per MW capacity) and a new confidential source (F_N). The auxiliary fuel types and their respective material requirements were in the old source, but not the new. The old fuel mix was thus modified using the ratio of the old and new requirement (F_N/F_O).

$$m_N = m_O(F_N/F_O)$$

A1.11 SUMMARY OF DATA SOURCES FOR THE SUSTAINABILITY ASSESSMENT

The data collected allow the production of sustainability indicators for electricity generation systems, which consume Australian fossil fuels. These tables allow the duplication of the data shown in Chapter 4.

APPENDIX 2: EXAMPLES OF SUSTAINABILITY INDICATOR PRODUCTION STEPS

A2.1 OVERVIEW OF EXAMPLES OF SUSTAINABILITY INDICATOR CALCULATION STEPS

This appendix contains details and examples of the calculation methods for the sustainability indicator methods. Section A2.2 details the methods used to convert the subsystem basis data of Chapter 4 into the system basis. Section A2.3 details the process of normalisation.

A2.2 BASIS CONVERSION AND CONVERSION FACTORS

A2.2.1 Material Flows

A2.2.1.1 Conversion Data

Section 4.3.6.2.1 describes the method for producing conversion data to change the basis of data from subsystem to system. For example: BIC, ST system.

The method requires the material flow data of the basis material for each subsystem (see Table data from Section 4.3.2). The rates 'To' refer to the flow of the reference substance required by the subsystem named in the 'Subsystem' column ($m_{BS,Subsystem,To}$). The rates 'from' refer to the flow of the reference substance from the subsystem named in the 'Subsystem' column ($m_{BS,Subsystem,From}$). The qualifier 'to be' indicates that the basis is an input material flow.

Subsystem	Basis Substance	Rates To		Rates From	
Mining	Black Coal			1 x 10^9	kg per Mtpa mined
Transport	Black Coal	1 x 10^9	kg per Mtpa to be transported	9.98 x 10^8	kg per Mtpa to be transported
Generation	Electricity	4.49 x 10^5	kg per GWh generated	1	GWh per GWh generated
Transmission	Electricity	1	GWh per GWh to be delivered	0.986	GWh per GWh to be delivered
System	**Electricity**			**1**	**GWh per GWh delivered**

Step 1: Convert the transmission (Trm) basis into the system (Sys) basis.

Transmission data has 'to be' in its units, and thus has an input basis. Conversion to output basis involves division of the input by the system output.

$$F_{BS-S,Trm} = \frac{m_{BS,Trm,To}}{m_{BS,Trm,From}} = \frac{1}{0.986} = 1.01 \text{ GWh to be delivered per GWh delivered}$$

This $F_{BS-S,Trm}$ is the factor used to convert all transmission material flows into the system basis.

Step 2: Convert the generation (Gen) basis into the system basis.

Generation data is already in output basis, thus no conversion to output basis (see Step 1 as an example) is necessary.

$$F_{BS-S,Gen} = \frac{1}{m_{BS,Gen,From}}\left(\frac{m_{BS,Trm,To}}{m_{BS,Trm,From}}\right) = \frac{1}{m_{BS,Gen,From}}\left(F_{BS-S,Trm}\right) = 1 x 1.01$$

$$= 1.01 \text{ GWh generated per GWh delivered}$$

As in Step 1, this $F_{BS-S,Gen}$ factor is used to convert all generation material flows into the system basis.

Step 3: Convert the transport (Tsp) basis into the system basis.

Transport data is in input basis, and thus conversion to output basis is necessary.

$$F_{BS-S,Tsp} = \left(\frac{m_{BS,Tsp,To}}{m_{BS,Tsp,From}}\right)\frac{1}{m_{BS,Gen,From}}\left(\frac{m_{BS,Trm,To}}{m_{BS,Trm,From}}\right) = \left(\frac{1 x 10^9}{9.98 x 10^8}\right) x 1 x 1.01$$

$$= 1.02 \text{ GWh generated per GWh delivered}$$

The basis of the transport subsystem is Mt to be transported (see table above), not GWh generated. Conversion uses the rate of coal required per GWh of electricity generated.

$$F_{BS-S,Tsp} = F_{BS-S,Tsp} \cdot m_{BS,Gen,Required} = \frac{4.59 x 10^5 \text{ kg/GWh}}{10^9 \text{ kg/Mt}} x 1.02 \text{ GWh/GWh}$$

$$= 4.56 x 10^{-4} \text{ Mt to be transported per GWh delivered}$$

This $F_{BS-S,Tsp}$ factor is used to convert all transport material flows into the system basis.

Step 4: Convert the mining (Min) basis into the system basis.

Mining data is already in output basis, thus no conversion to output basis is necessary.

$$F_{BS-S,Min} = \frac{1}{m_{BS,Min,From}}\left\{\left[\left(\frac{m_{BS,Tsp,Required}}{m_{BS,Tsp,From}}\right)\frac{1}{m_{BS,Gen,From}}\right]\left(\frac{m_{BS,Gen,Required}}{10^9}\right)\right\}\left(\frac{m_{BS,Trm,To}}{m_{BS,Trm,From}}\right)$$

$$= \left(\frac{1}{m_{BS,Min,From}} \right) F_{BS-S,Gen}$$

$$= 4.56 \times 10^{-4} \text{ Mt to be transported per GWh delivered}$$

This $F_{BS-S,Min}$ factor is used to convert all generation material flows into the system basis (except for the NG mining subsystem (see Section A2.2.1.2)).

A2.2.1.2 Producing System Material Flow Data

Producing allocation factors:

For fuel gas allocation of NG mining subsystem:

Section A1.9.5.3 (Appendix 1) contains the derivation of the relative fuel-gas consumption factors for natural gas and LNG (P_{NG} and P_{LNG}). Producing the allocation factors, shown in Section 4.3.5.2, for the NG mining stage from these factors requires two steps. Step 1 converts the P_{NG} and P_{LNG} values into percentages[*]:

$$\% P_{NG} = \left(\frac{P_{NG}}{m_{FuelGas,Min}} \right) m_{NG,Min} = \left(\frac{0.0410}{2408} \right) 13201 = 22.5\%$$

$$\begin{aligned} \text{where}: m_{FuelGas,Aust,Min} &= P_{NG} . m_{NG,Aust,Min} + P_{LNG} . m_{LNG,Aust,Min} + P_{Liquids} . m_{Liquids,Aust,Min} \\ &= 0.0410 x 13201 + 0.106 x 7397 + 0.0363 x 29834 \\ &= 2408 \end{aligned}$$

Step 2 uses this percentage to produce the allocation for the yearly averaged natural gas and petroleum productions (15164 kt and 51143 kt)[†] to produce the allocation factor (F_A):

$$F_{A,Min,NG} = \left(\frac{\% P_{NG}}{m_{NG,Aust.Min}} \right) m_{Petroleum,Aust.Min} = \left(\frac{22.5\%}{15164} \right) 51143$$

$$= 0.758 \frac{\text{material flows per kg natural gas}}{\text{material flows per kg petroleum}}$$

The same process applies for LNG systems.

[*] P_i from Section A1.9.5.3, Appendix 1 and $m_{i,Aust,Min}$ are yearly averages from APPEA (2000).

[†] $m_{NG,Aust,Min}$ and $m_{Petroleum,Aust,Min}$ are yearly averages from APPEA (2000).

This factor is then multiplied with the $F_{B-S,Min}$ factor produced in Section A2.2.1.1 to generate an allocated conversion factor, $F_{B-S,Min,A}$.

For economic allocation of NG and BIC mining subsystems:

NG mining: Relative economics of products from ABS (2001), relative production from APPEA (1999).

Product	$/kg product	m_i (Mtpa)	$ per kg petroleum	P_i (%)
Crude Oil	0.160	21.8	0.0691	45.7
Condensate	0.0947	5.8	0.0101	7.21
Natural Gas	0.132	13.2	0.0346	22.8
LPG	0.224	2.22	0.00985	6.52
LNG	0.182	7.4	0.0267	17.7
Total		50.4	0.151	100

For example (NG):

$$\left(\frac{\$}{\text{kg petroleum}} \right)_{NG} = \left(\frac{\$}{\text{kg product}} \right)_{NG} \frac{m_{NG,Aust.Min}}{m_{Petroleum,Aust.Min}} = (0.132) \frac{13.2}{50.4} = 0.0346$$

$$P_{NG} = \frac{\left(\frac{\$}{\text{kg petroleum}} \right)_{NG}}{\left(\frac{\$}{\text{kg petroleum}} \right)_{NG}} = \frac{0.0346}{0.151} = 22.8\%$$

Production of allocation factors from this P_{NG} factor is identical to Step 2 of the fuel gas allocation method.

BIC mining: Relative economics of BIC to BICE from Simes (2000).

<table>
<tr><th>Fuel</th><th>Description</th><th>Value</th><th>Units</th></tr>
<tr><td rowspan="3">BIC</td><td>% of coal for domestic consumption</td><td>43</td><td>% by mass</td></tr>
<tr><td rowspan="2">Relative Cost</td><td>75</td><td>% BIC value of BICE value</td></tr>
<tr><td>37.3</td><td>% value of BIC of 1 t of All Coal</td></tr>
<tr><td rowspan="3">BICE</td><td>% of coal for export</td><td>57</td><td>% by mass</td></tr>
<tr><td rowspan="2">Relative Cost</td><td>100</td><td>% BICE value of BICE value</td></tr>
<tr><td>62.7</td><td>% cost of BICE of 1 t of All Coal</td></tr>
<tr><td rowspan="2">All Coal</td><td rowspan="2">Relative Cost</td><td>90.2</td><td>% All Coal value of BICE value</td></tr>
<tr><td>100</td><td>% cost of All Coal of 1 t of All Coal</td></tr>
</table>

$$\%\text{ cost of BIC for 1 t of All Coal} = \frac{(\%\text{ cost of BIC compared to BICE})(\text{BIC \% by mass})}{(\%\text{ cost of BIC compared to BICE})(\text{BIC \% by mass}) + (\%\text{ cost of BICE compared to BICE})(\text{BICE \% by mass})}$$

The allocation factors ($F_{BIC,Min}$ and $F_{BICE,Min}$) are obtained as:

$$F_{A,BIC,Min} = \frac{\%\text{ cost of BIC for 1 t of All Coal}}{\text{BIC \% by mass}} = \frac{37.3}{43} = 0.859$$

$$F_{A,BIC,Min} = \frac{\%\text{ cost of BIC for 1 t of All Coal}}{\text{BIC \% by mass}} = \frac{62.7}{57} = 1.11$$

Producing system basis material flow data:

Example: Diesel consumption in BIC-ST system

Subsystem	Rates	
Mining	1.5×10^{6}	kg per Mtpa mined
Transport	7.36×10^{5}	kg per Mtpa to be transported
Generation	9.1	GWh per GWh generated
Transmission	0	GWh per GWh to be delivered

Thus, using the conversion factors ($F_{BS-S,i}$) from Section A2.2.1.1:

$$m_{Diesel,S} = m_{Diesel,Min} \times F_{BS-S,Min} + m_{Diesel,Tsp} \times F_{BS-S,Tsp} + m_{Diesel,Gen} \times F_{BS-S,Gen} (+ m_{Diesel,Trm} \times F_{BS-S,Trm})$$
$$= (1.5 \times 10^{6} \times 4.56 \times 10^{-4}) + (7.36 \times 10^{5} \times 4.56 \times 10^{-4}) + (9.1 \times 1.01)(+ 0 \times 1.01)$$
$$= 1028 \text{ kg per GWh delivered}$$

Similarly for electricity consumption in BIC-ST system:

Subsystem	Rates		
	Consumed	Emitted	Units
Mining	19.7	0	GWh per Mtpa mined
Transport	0.508	0	kg per Mtpa to be transported
Generation	5.67	1.06	GWh per GWh generated
Transmission	1	0.986	GWh per GWh to be delivered
System	1.08	2.08	GWh per GWh delivered

If an allocation procedure was used for the subsystem, such as for the natural gas mining system, the allocated conversion factor ($F_{BS-S,i,A}$) replaces the conversion factor ($F_{BS-S,i}$) in the above procedure.

Removing electricity from the material flow data:

Using the technique established in Section A2.2.1.2, 'Producing system basis material

flow data', allows the generation of a table of diesel and electricity consumption and emission data in the system basis (kg per GWh delivered):

Consumption	Subsystem				
	Mining	Transport	Generation	Transmission	System
Electricity	8.98×10^{3}	2.3×10^{4}	5.75×10^{-2}	1.01	1.07
Diesel	686	332	10.1	0	1028
Emission	**Mining**	**Transport**	**Generation**	**Transmission**	**System**
Electricity	0	0	1.07	1	2.07
Diesel	0	0	0	0	0

Step 1: Assume all of generation electricity consumption is internal (only startup power would be sourced from the grid). Remove transmission systems electricity carriage (1 MW enters and leaves). Thus, the system consumes 1028 kg of diesel and 2.28×10^{-2} GW of electricity to deliver 1 GWh of electricity.

Consumption	Subsystem				
	Mining	Transport	Generation	Transmission	System
Electricity	8.98×10^{-3}	2.3×10^{-4}	0	1.39×10^{-2}	2.28×10^{-2}
Diesel	686	332	10.1	0	1028
Emission	**Mining**	**Transport**	**Generation**	**Transmission**	**System**
Electricity	0	0	0	1	1
Diesel	0	0	0	0	0

Step 2: Replace electricity consumption with an equivalent amount of consumption and emissions. For the mining subsystem 8.98×10^{3} GWh of electricity is required. 1 GWh of electricity consumes 1028 kg of diesel and 2.28×10^{-2} GW of electricity. Thus, 8.98×10^{-3} GWh of electricity consumes 9.23 kg of diesel and 2.06×10^{-4} GWh of electricity. Continuing this substitution for all subsystems gives:

Consumption	Subsystem				
	Mining	Transport	Generation	Transmission	System
Electricity	2.06×10^{-4}	5.31×10^{-6}	0	3.13×10^{-4}	5.24×10^{-4}
Diesel	696	332	10.1	14.1	1052
Emission	**Mining**	**Transport**	**Generation**	**Transmission**	**System**
Electricity	0	0	0	1	1
Diesel	0	0	0	0	0

Step 3: Repeat Step 2 by iteration or matrix inversion methods until the electricity consumptions are zero.

Consumption			Subsystem		
	Mining	Transport	Generation	Transmission	System
Electricity	0	0	0	0	0
Diesel	696	332	10.1	14.6	1053
Emission	**Mining**	**Transport**	**Generation**	**Transmission**	**System**
Electricity	0	0	0	1	1
Diesel	0	0	0	0	0

The process is identical for all other systems, and materials.

A2.2.1.3 Producing Environmental Indicators

Producing environmental indicators uses Equation 3.2.4. For example: World resource depletion (RD W) for BIC, ST subsystem. This table shows the converted material flows data for black coal and diesel.

Consumption (kg per GWh)			Subsystem		
	Mining	Transport	Generation	Transmission	System
Black Coal	4.61×10^5	108	0	6490	4.67×10^5
Diesel	696	332	10.1	14.6	1053

The characterisation factors, $CF_{RD\ W,c}$, for black coal (0.0134 $kg_{Sb\text{-}eq.}$ per kg black coal) and diesel (0.0201 $kg_{Sb\text{-}eq.}$ per kg diesel, assumes equivalent to oil) are from Guinée *et al.* (2001). Using Equation 3.2.4 gives:

$$ICS_{RD\ W} = RD\ W = m_{RD\ W,Black\ Coal}\ x\ CF_{RD\ W,Black\ Coal} + m_{Diesel}\ x\ CF_{RD\ W,Diesel}$$

$$= 4.67 \times 10^5\ x\ 0.0134 + 1053\ x\ 0.0201$$

$$= 6280\ kg_{Sb\text{-}eq.}\ \text{per GWh delivered}$$

A2.2.2 Economic Flows

A2.2.2.1 Producing subsystem I and O&M costs

I and O&M costs are correlations (see Section A1.9.4.1, Appendix 1, for information on producing correlated costs) based on an estimated capacity (Q) for I or production (P) for O&M. For example: BIC generation subsystem, I costs. The capital cost function for this subsystem is Equation 4.3.20. The assumed capacity for the system is 1000

MW, which means the required capacity for the generation subsystem ($Q_{BIC,Gen}$) is 1014 MW (see Section A2.2.2.5). Using Equation 4.3.20:

$$I_{BIC,Gen} = 12.5(Q_{BIC,Gen})^{0.663} = 12.5(1014)^{0.663} = \$1230\ \text{million (AUD 2000)}$$

A2.2.2.2 Producing subsystem I and O&M costs using Equation 4.3.48

Some subsystem costs assume a larger capacity than that required, i.e. BIC mining, and NG mining and transport, as present systems also supply other markets (BIC for domestic and export use, NG for electricity and domestic and industrial heat and energy). Equation 4.3.48 allows this to be included. For example: BICE mining subsystem, I costs. The capital cost function for this subsystem is Equation 4.3.3. The assumed capacity for the system is 1000 MW, which means the required capacity for the mining subsystem ($Q_{BIC,Min}$) is 2.32 Mtpa (see Section A2.2.2.5). Using Equation 4.3.3:

$$I_{BIC,Min} = 130(Q_{BIC,Min})^{0.690} + 90.0(Q_{BIC,Min})^{0.616}$$

A survey of power stations and mines shows that each power station has an average of 2.67 distinct mines. Of these mines, 43.4 % of coal was for domestic consumption. Assuming each of these mines is of equal size, then the total amount of coal produced for 2.32 Mtpa of domestic coal is 2.32/0.434 = 5.35 Mtpa. 2.67 distinct mines (DM) produce this 5.35 Mtpa, and thus each mine produces 5.35/2.67 = 2.01 Mtpa. Thus each mine costs:

$$(I_{BIC,Min})_{DM} = 130(Q_{BIC,Min,DM})^{0.690} + 90.0(Q_{BIC,Min,DM})^{0.616} = 130(2.01)^{0.690} + 90.0(2.01)^{0.616}$$

$$= \$349\ \text{million (AUD 2000)}$$

2.67 of these mines ($(I_{BIC,Min})_{DMT}$) cost $ 931 million (AUD 2000). Equation 4.3.48 estimates the proportion due to domestic consumption:

$$I_{BIC,Min} = (I_{BIC,Min})_{DMT} \frac{Q}{(Q)_{DMT}} = 931\frac{2.32}{5.35} = \$\ 404\ \text{million (AUD 2000)}$$

This value assumes, for simplicity of explanation, that each mine is of the same size. In the actual calculation, 2 mines are assumed to provide 62 % of coal by conveyor, 0.3 mines provide 16 % by road, and 0.37 mines provide 22 % by rail. However, the same method applies. For BICE, 0.3 mines provide 11 % by road, while 2.37 mines provide 89 % by rail.

A2.2.2.3 Producing a subsystem VA indicator

Producing subsystem VA indicators requires sales (S), upstream purchases (F), labour costs (L) and operating and maintenance (O&M) values. S, F and L values are in Section 4.3.5.3.1, while O&M costs come from various correlations in Section 4.3 (see 'Producing a subsystem I/O&M cost' for information on producing O&M values from these correlations). Equation 3.3.3 gives VA as:

$$VA = \sum_{l=1}^{L}\sum_{s=1}^{S}\{S_{s,l} - [(O\&M_{s,l} + F_{s,l}) - L_{s,l}]\}$$

For a single subsystem, s, and a single year, l, then Equation 3.3.3 becomes:

$$VA_s = S_s - [(O\&M_s + F_s) - L_s]$$

For example: BIC generation subsystem. In this example, $S_{BIC,Gen}$ = \$ 39.9 (AUD 2000) per MWh, $F_{BIC,Gen}$ (previous subsystem's, S or $S_{BIC,Tsp}$) = \$ 40.6 (AUD 2000) per t, $L_{BIC,Gen}$ = 42.1 % of O&M, and $O\&M_{BIC,Gen}$ = \$ 9.41 (AUD 2000) per GWh.

Step 1: $F_{BIC,Gen}$ is converted to the current basis by multiplying with the amount of BIC consumed to generate 1 MWh of electricity from the generation stage. This requires multiplication by the transport subsystem conversion factor ($F_{BS\text{-}S,Tsp}$ = 4.56 x 10^{-4}) and division by the generation factor ($F_{BS\text{-}S,Tsp}$ = 1.01) (see 'Producing system I, NPC, VA and CVA indicators'). Thus, $F_{BIC,Gen}$ = \$ 18.3 (AUD 2000) per MWh.

Step 2:

$$\begin{aligned} VA_{BIC,Gen} &= S_{BIC,Gen} - [(O\&M_{BIC,Gen} + F_{BIC,Gen}) - L_{BIC,Gen}] \\ &= S_{BIC,Gen} - [(O\&M_{BIC,Gen} + F_{BIC,Gen}) - L_{BIC,Gen}(O\&M_{BIC,Gen})] \\ &= 39.9 - [(9.41 + 18.3) - 0.421(9.41)] \\ &= \$16.5\ \text{(AUD 2000) per MWh} \end{aligned}$$

A2.2.2.4 Producing subsystem C_R, NPC and CVA indicators

Producing subsystem C_R indicators requires capital costs (I), cost of capital (i) and life of loan (n) values. i and n values are in Section 4.3.6.3.1, while I values come from various correlations in Section 4.3 (see 'Producing a subsystem I/O&M cost' for information on producing I values from these correlations). Equation 3.3.8 gives C_R as:

$$C_R = \frac{I.i}{\left[1 - \frac{1}{(1+i)^n}\right]}$$

Producing subsystem NPC indicators requires annualised capital repayment (C_R) and operating costs (O&M) values. For C_R values see above and for O&M values (see 'Producing a subsystem I/O&M cost'). Equation 3.3.12 gives NPC as:

$$NPC = O\&M + C_R$$

Producing subsystem CVA indicators requires annualised capital repayment (C_R) and value added (VA) values. For C_R values see above and for VA values (see 'Producing a subsystem VA indicator'). Equation 3.3.14 gives CVA as:

$$CVA = VA - C_R$$

For example: BIC generation subsystem. In this example, I = \$ 1230 million (AUD 2000) (see 'Producing a subsystem I/O&M cost'), O&M = \$ 9.41 million (AUD 2000), VA = 16.5 (AUD 2000) per MWh (see 'Producing a subsystem VA indicator'), i = 6.2 % and n = 30 years.

$$C_R = \frac{I.i}{\left[1 - \frac{1}{(1+i)^n}\right]} = \frac{(1230)(0.062)}{\left[1 - \frac{1}{(1+0.062)^{30}}\right]} = \$91.3\ \text{million (AUD 2000) per annum}$$

Dividing by the system yearly production at 1014 MW (P_{BIC} = 5089 GWhpa) gives C_R = \$ 17.9 (AUD 2000) per MWh. Thus:

$$NPC = O\&M + C_R = 9.41 + 17.9 = \$27.3\ \text{(AUD 2000) per MWh}$$

$$CVA = VA - C_R = 16.5 - 17.9 = \$-1.44\ \text{(AUD 2000) per MWh}$$

A2.2.2.5 Producing system I, NPC, VA and CVA indicators

The method is similar to that of material flows (see Section A2.2.1.2, 'Producing system basis material flow data'). However, unlike the material flows, the assumed capacity and production undergo conversion, not the subsystem indicators produced. This is because for economic data, the assumed capacity or production is the independent parameter in their correlations. The system indicators are thus the sum of the subsystem value produced using the converted capacities and productions. For example: BIC-ST system capacities and productions. Mass flows BIC conversion factors (see Section A2.2.1.1):

Subsystem	Conversion Factors
Mining	4.56×10^{-4}
Transport	4.56×10^{-4}
Generation	1.01
Transmission	1.01

Assumed system capacity ($Q_{BIC,S}$) is 1000 MW. Assuming an average production time (load factor) of 58.1 % (for Australian BIC-ST systems), then:

$$P_{BIC,S} = Q_{BIC,S}.LF_{BIC}.t(\text{hours per year}) = \frac{1000}{1000}(0.581)(24 x 365) = 5089\,\text{GWhpa}$$

The capacity (Q) or production (P) are multiplied by the conversions:

For example:

$$Q_{BIC,Min} = Q_{BIC,S}.F_{A,BIC,Min} = 1000(4.56 \times 10^{-4}) = 2.32\,\text{Mtpa}$$

Subsystem	Q	P
Mining	2.32 Mtpa	2.32 Mtpa
Transport	2.32 Mtpa	2.32 Mtpa
Generation	1014 MW	5159 GWhpa
Transmission	1014 MW	5159 GWhpa
System	1000 MW	5089 GWhpa

A2.2.3 Social Flows

A2.2.3.1 Producing a EI from a ED

Indirect employment (EI) production uses direct employment (ED) and multipliers (EM). Equation 3.4.2 gives EI as:

$$EI = \sum_{s=1}^{S_T}\sum_{c=1}^{C_T} EM_c \, x \, ED_{s,c}$$

For a single subsystem, s, then:

$$EI_s = \sum_{c=1}^{C_T} EM_c \, x \, ED_{s,c}$$

Most subsystems have only one type of industry classification, except transport,

where road, rail and pipeline, and ocean transport have different classifications. For example: BIC, ST generation. In this subsystem, ED is 2.71×10^{-5} employees per MWhpa, and its industry classification is electricity. The EM for electricity is 4.275 indirect employees per direct employee. Thus:

$$EI_{BIC,Gen} = \sum_{c=1}^{1} EM_c \, x \, ED_{BIC,Gen,c} = 4.275 x 2.71 \times 10^{-5}$$

$$= 1.16 \times 10^{-4} \text{ indirect employees per MWh}$$

A2.2.3.2 Producing system ED, EI, LTI and Fatal indicators

The method is the same as that of material flows (see Section A2.2.1.2, 'Producing system basis material flow data').

A2.3 NORMALISATION

Normalisation is the division of an indicator score (ICS_a) by a regional indicator score (ICS_a^R) (Equation 3.2.5). For example: BIC, ST system, RD W score. $ICS_{RD\,W}$ for the BIC, ST system 6.29 kg $Sb_{.eq.}$ per MWh of electricity delivered (see Table 5.2.1). $ICS_{RD\,W}^{Australia}$ for the Australian region is 4.80×10^9 kg $Sb_{.eq.}$ per annum. Thus:

$$ICS_{RD\,W}^{Australia,N} = \frac{ICS_{RD\,W}}{ICS_{RD\,W}^{Australia}} = \frac{6.29}{4.80 \times 10^9} = 1.31 \times 10^{-9} \frac{\text{kg Sb}_{.eq.}\text{ per MWh delivered}}{\text{kg Sb}_{.eq.}\text{ per MWh delivered}}$$

A2.4 NG RESOURCE LIFE UNDER ALL CCGT-NG SCENARIO

Electricity production information for Australia is available from ESAA (1999) in Table 2.4 and Chart 2.5. The table below shows the generation information (GWhpa) obtained from these charts. The NG figure for ST assumes that the contribution of other petroleum fuels to OCGT and CCGT generation is minimal.

Fuel	Technology			
	ST	OCGT	CCGT	Total
NG	7870	1540	931	1.03×10^4
BIC	9.91×10^4			9.91×10^4
BrC	5.40×10^4			5.40×10^4
Hydro				1.52×10^4
All	1.61×10^5	1540	931	1.63×10^5

This NG electricity generation consumes 98.782 PJpa of natural gas (ESAA (1999),

Table 2.5). Australian natural gas consumption in 2000 was 1218.7 PJpa (AGA (2001)). Thus, non-electricity requirements are 1120 PJpa.

To provide all, non-hydro electricity, CCGT-NG plants must provide 1.48 x 10^5 GWhpa. The natural gas requirements for each GWh of electricity are 1.59 x 10^5 kg (Table 4.3.41, Chapter 4). Thus, the CCGT-NG systems would require 2.35 x 10^{10} kg of NG. Using a natural gas energy density of 39 MJ per m^3 (IOR Energy Pty Ltd (2000)) and mass density of 0.762 (NPI (1999)) then, 2.35 x 10^{10} kg of NG is 1205 PJpa. Thus, the total NG requirements would be the non-electricity requirements (1120 PJpa) plus the CCGT-NG requirements (1205 PJpa), or 2325 PJpa. The total reserve in 2000 was 127928 PJ (AGA (2001)). Thus, the NG reserve life under this condition is 55 years (127928/2325 years).

A2.5 Summary of Examples of Sustainability Indicator Calculation Steps

These examples allow the duplication of the results shown in Chapter 5.

Appendix 3: Contributions and Normalised Sustainability Indicators

A3.1 Overview of Contributions and Normalised Sustainability Indicators

Section A3.2 contains the actual contributions of subsystems to the total indicators, shown in Chapter 5 as Figures 5.2.1, 5.3.1 and 5.4.1. Section A3.3 contains the normalised sustainability indicators, shown in Chapter 5 as Figure 5.5.1.

A3.2 Subsystem Indicator Contribution Tables

Table of environmental indicator subsystem contributions (Units (all per MWh of electricity delivered): CC = climate change (kg $CO_{2\text{-eq}}$); AD = acidification (kg $SO_{2\text{-eq}}$); EU = eutrophication (kg $PO_4^{3-}{}_{\text{-eq}}$); PS = photochemical smog (kg $C_2H_{4\text{-e}}$); HT and ET = human and eco-toxicity (kg 1,4-dichlorobenzene); PM and SW = particulates and solid waste emissions (kg); WD = water consumption (t); RD A and RD W = Australian and world resource depletion (kg $Sb_{\text{-e}}$); and EN and EX = energy consumption and exergy destruction (GJ)).

Fuel	Tech.	Sub.	Indicator					
			CC	AD	EU	PS	HT	ET	PM
BIC	ST	Min.	45.4	0.0831	7.96 x 10^{-3}	0.015	55.3	0.0829	6.20 x 10^{-3}
		Tsp.	1.3	0.0127	2.05 x 10^{-3}	1.31 x 10^{-3}	5.12	0.0613	0.0511
		Gen.	999	6.5	0.421	0.294	5130	4.69	0.483
		Trn.	14.7	0.0928	6.07 x 10^{-3}	4.36 x 10^{-3}	73.1	0.068	7.61 x 10^{-3}
	IGCC	Min.	26	0.0212	3.97 x 10^{-3}	0.0107	6.27	0.0386	1.49 x 10^{-3}
		Tsp.	0.971	6.29 x 10^{-3}	1.10 x 10^{-3}	9.59 x 10^{-4}	2.2	0.0339	0.0287
		Gen.	647	0.141	0.0206	7.40 x 10^{-3}	65.1	0.212	7.28 x 10^{-3}
		Trn.	9.48	2.37 x 10^{-3}	3.62 x 10^{-4}	2.68 x 10^{-4}	1.04	4.01 x 10^{-3}	5.28 x 10^{-4}
BICE	ST	Min.	67.5	0.131	0.012	0.0226	88.8	0.136	0.0157
		Tsp.	29.3	0.612	0.019	0.0293	528	1.02	0.535
		Gen.	999	6.5	0.421	0.294	5130	4.69	0.483
		Trn.	15.4	0.102	6.37 x 10^{-3}	4.86 x 10^{-3}	80.9	0.0822	0.0145
	IGCC	Min.	37.3	0.0307	5.35 x 10^{-3}	0.0141	10.8	0.0537	3.98 x 10^{-3}
		Tsp.	15.5	0.397	0.0321	0.0235	289	0.564	0.299
		Gen.	647	0.141	0.0206	7.40 x 10^{-3}	65.1	0.212	7.28 x 10^{-3}
		Trn.	9.84	8.01 x 10^{-3}	8.17 x 10^{-4}	6.34 x 10^{-4}	5.13	0.0117	4.37 x 10^{-3}
BrC	ST	Min.	7.66	0.0221	1.88 x 10^{-3}	1.26 x 10^{-3}	15.7	0.0213	3.16 x 10^{-3}
		Tsp.	1.11	2.86 x 10^{-3}	2.00 x 10^{-4}	1.36 x 10^{-4}	2.21	2.46 x 10^{-3}	5.22 x 10^{-4}

Fuel	Tech.	Sub.	Indicator						
			CC	AD	EU	PS	HT	ET	PM
BrC	ST	Gen.	1180	3.04	0.211	0.143	2340	2.54	0.479
		Trn.	26.5	0.0683	4.76×10^{-3}	3.23×10^{-3}	52.6	0.0572	0.0108
	IGCC	Min.	4.89	0.0166	1.95×10^{-3}	4.25×10^{-3}	9.59	0.0195	7.48×10^{-4}
		Tsp.	0.649	1.16×10^{-3}	1.35×10^{-5}	3.14×10^{-4}	1.16	3.16×10^{-4}	1.18×10^{-4}
		Gen.	728	2.34	0.0219	0.0977	2370	0.411	0.0204
		Trn.	16.4	0.0525	5.31×10^{-4}	2.28×10^{-3}	53.1	9.60×10^{-3}	4.75×10^{-4}
NG	ST	Min.	67.4	0.21	0.0447	0.106	40.2	0.433	0.0166
		Tsp.	8.31	4.21×10^{-4}	8.35×10^{-5}	7.49×10^{-3}	0.107	2.43×10^{-3}	2.00×10^{-3}
		Gen.	647	0.733	0.191	0.0445	1.82	1.77	0.0164
		Trn.	0.816	1.06×10^{-3}	2.66×10^{-4}	1.78×10^{-4}	0.0476	2.49×10^{-3}	3.95×10^{-5}
	OCGT	Min.	90.1	0.28	0.0597	0.141	53.7	0.578	0.0222
		Tsp.	11.1	6.56×10^{-4}	1.35×10^{-4}	0.01	0.147	3.51×10^{-3}	2.72×10^{-3}
		Gen.	745	1.19	0.308	0.0766	6.93	3.06	0.26
		Trn.	0.955	1.66×10^{-3}	4.15×10^{-4}	2.57×10^{-4}	0.0686	4.11×10^{-3}	3.22×10^{-4}
	CCGT	Min.	47.2	0.147	0.0313	0.0739	28.2	0.303	0.0116
		Tsp.	5.8	2.46×10^{-4}	4.60×10^{-5}	5.24×10^{-3}	0.0745	1.59×10^{-3}	1.40×10^{-3}
		Gen.	405	0.267	0.0683	0.0189	5.28	0.659	0.0242
		Trn.	0.517	4.68×10^{-4}	1.12×10^{-4}	1.11×10^{-4}	0.0379	1.09×10^{-3}	4.20×10^{-5}
LNG	ST	Min.	198	0.616	0.131	0.31	118	1.27	0.0487
		Tsp.	32.5	0.0945	0.0105	0.0146	56.9	0.108	6.26×10^{-3}
		Gen.	647	0.733	0.191	0.0445	1.82	1.77	0.0164
		Trn.	0.99	1.63×10^{-3}	3.75×10^{-4}	4.16×10^{-4}	0.2	3.56×10^{-3}	8.05×10^{-5}
	OCGT	Min.	265	0.823	0.175	0.414	158	1.7	0.0651
		Tsp.	44	0.129	0.0146	0.02	76.2	0.15	9.22×10^{-3}
		Gen.	745	1.19	0.308	0.0766	6.93	3.06	0.26
		Trn.	1.19	2.42×10^{-3}	5.62×10^{-4}	5.76×10^{-4}	0.272	5.54×10^{-3}	3.77×10^{-4}
	CCGT	Min.	139	0.432	0.092	0.217	82.7	0.891	0.0341
		Tsp.	22.2	0.065	7.10×10^{-3}	0.01	39.8	0.0731	4.37×10^{-3}
		Gen.	405	0.267	0.0683	0.0189	5.28	0.659	0.0242
		Trn.	0.638	8.62×10^{-4}	1.89×10^{-4}	2.78×10^{-4}	0.144	1.83×10^{-3}	7.07×10^{-5}

Table of environmental indicator subsystem contributions (continued).

Fuel	Tech.	Sub.	Indicator					
			SW	WD	RD A	RD W	EN	EX
BIC	ST	Min.	0.784	0.33	0.405	6.19	11.1	13.3
		Tsp.	0.0707	5.49×10^{-4}	0.181	8.13×10^{-3}	0.0177	0.0183
		Gen.	85.3	2	0.178	6.58×10^{-3}	0.0141	0.121
		Trn.	1.21	0.0328	0.0107	0.0873	0.157	0.19

Fuel	Tech	Sub.	Indicator					
			SW	WD	RD A	RD W	EN	EX
BIC	IGCC	Min.	0.318	0.18	0.421	3.66	6.45	7.88
		Tsp.	0.0368	1.75×10^{-4}	0.102	4.25×10^{-3}	9.40×10^{-3}	9.63×10^{-3}
		Gen.	61.8	1.1	0.0122	4.52×10^{-4}	1.03×10^{-3}	0.249
		Trn.	0.874	0.018	7.53×10^{-3}	0.0515	0.0909	0.115
BICE	ST	Min.	4.1	0.49	0.662	9.15	16.4	19.7
		Tsp.	216	0.121	4.81	0.2	0.424	0.452
		Gen.	85.3	2	0.178	6.58×10^{-3}	0.0141	0.121
		Trn.	4.3	0.0368	0.0795	0.132	0.237	0.286
	IGCC	Min.	1.39	0.266	0.547	5.31	9.4	11.6
		Tsp.	121	0.0661	2.54	0.101	0.216	0.263
		Gen.	61.8	1.1	0.0122	4.52×10^{-4}	1.03×10^{-3}	0.337
		Trn.	2.6	0.0202	0.0436	0.0761	0.135	0.171
BrC	ST	Min.	0.132	5.89×10^{-4}	0.0766	9.6	13.6	12
		Tsp.	0.027	2.17×10^{-3}	1.69×10^{-4}	8.99×10^{-3}	0.0127	0.0113
		Gen.	21.2	2.62	0.104	3.89×10^{-3}	8.30×10^{-3}	0.0587
		Trn.	0.476	0.0517	4.03×10^{-3}	0.214	0.304	0.27
	IGCC	Min.	0.0434	7.37×10^{-4}	0.235	5.15	7.25	6.62
		Tsp.	0.0102	2.43×10^{-4}	3.29×10^{-4}	2.52×10^{-3}	3.56×10^{-3}	3.28×10^{-3}
		Gen.	13.3	0.646	3.39×10^{-3}	1.25×10^{-4}	2.89×10^{-4}	0.0781
		Trn.	0.298	0.0105	5.33×10^{-3}	0.115	0.162	0.149
NG	ST	Min.	0.0211	5.06×10^{-4}	5.53	5.57	6.89	11.8
		Tsp.	2.79 x 10-6	0.0184	6.73×10^{-3}	9.59×10^{-4}	1.42×10^{-3}	2.08×10^{-3}
		Gen.	2.25×10^{-4}	139	5.85×10^{-3}	2.69×10^{-4}	5.81×10^{-4}	0.037
		Trn.	2.38×10^{-5}	0.157	6.25×10^{-3}	6.29×10^{-3}	7.78×10^{-3}	0.0134
	OCGT	Min.	0.0282	6.76×10^{-4}	7.38	7.44	9.21	15.8
		Tsp.	4.99 x 10-6	1.66 x 10-7	9.36×10^{-3}	1.61×10^{-3}	2.31×10^{-3}	3.48×10^{-3}
		Gen.	0	2.63×10^{-4}	0.184	6.82×10^{-3}	0.0146	0.0156
		Trn.	3.18×10^{-5}	1.06 x 10-6	8.55×10^{-3}	8.41×10^{-3}	0.0104	0.0179
	CCGT	Min.	0.0148	3.55×10^{-4}	3.87	3.9	4.83	8.3
		Tsp.	1.37 x 10-6	2.33×10^{-3}	4.57×10^{-3}	5.18×10^{-4}	8.03×10^{-4}	1.13×10^{-3}
		Gen.	1.74×10^{-5}	25.20	0.0958	3.55×10^{-3}	7.59×10^{-3}	0.0717
		Trn.	1.67×10^{-5}	0.0284	4.48×10^{-3}	4.41×10^{-3}	5.46×10^{-3}	9.45×10^{-3}
LNG	ST	Min.	0.0619	1.49×10^{-3}	6.93	6.28	7.8	13.4
		Tsp.	8.86×10^{-3}	4.17	4.11	0.167	0.342	0.376
		Gen.	2.25×10^{-4}	139	5.85×10^{-3}	2.69×10^{-4}	5.81×10^{-4}	0.037
		Trn.	7.99×10^{-5}	0.162	0.0125	7.27×10^{-3}	9.19×10^{-3}	0.0155
	GT	Min.	0.0828	1.99×10^{-3}	9.27	8.39	10.4	17.8
		Tsp.	0.0119	5.12	5.51	0.23	0.466	0.517

Fuel	Tech.	Sub.	Indicator					
			SW	WD	RD A	RD W	EN	EX
LNG	OC	Gen.	0	2.63×10^{-4}	0.184	6.82×10^{-3}	0.0146	0.0156
		Trn.	1.07×10^{-4}	5.78×10^{-3}	0.0169	9.74×10^{-3}	0.0123	0.0208
	CCGT	Min.	0.0434	1.04×10^{-3}	4.86	4.4	5.47	9.36
		Tsp.	6.17×10^{-3}	2.72	2.88	0.113	0.235	0.256
		Gen.	1.74×10^{-5}	25.2	0.0958	3.55×10^{-3}	7.59×10^{-3}	0.0717
		Trn.	5.60×10^{-5}	0.0315	8.84×10^{-3}	5.10×10^{-3}	6.45×10^{-3}	0.0109

Table of economic indicator subsystem contributions (I = capital cost ($ billion (AUD 2000)), AC, VA and CVA = annualised cost, value added and capital inclusive value added ($ (AUD 2000) per MWh of electricity delivered)).

Fuel	Tech.	SS	Indicator			
			I	AC	VA	CVA
BlC	ST	Min.	0.664	24.8	5.71	-3.97
		Tsp.	0.260	11.9	-0.327	-4.12
		Gen.	1.23	27.3	16.5	-1.44
		Trn.	0.137	2.82	20.8	18.8
BlC	IGCC	Min.	0.571	14.4	3.18	-2.68
		Tsp.	0.217	7.18	-0.522	-2.75
		Gen.	1.03	16.7	26.9	16.4
		Trn.	0.137	2.1	20.9	19.5
BlCE	ST	Min.	1.16	31.5	11.3	-0.634
		Tsp.	0.642	25.0	0.842	-5.75
		Gen.	1.23	20.7	47.0	34.3
		Trn.	0.137	2.1	14.8	13.4
	IGCC	Min.	0.794	19.3	6.25	-1.9
		Tsp.	0.417	17.3	-1.15	-5.44
		Gen.	1.60	22.5	59.8	43.4
		Trn.	0.137	2.1	14.8	13.4
BrC	ST	Min.	0.678	14.5	4.99	-1.97
		Tsp.	0.122	2.09	0	-1.25
		Gen.	2.17	26.9	31.2	8.95
		Trn.	0.214	2.88	21.1	18.9
	IGCC	Min.	0.476	9.99	3.37	-1.51
		Tsp.	0.0878	1.49	0	-0.902
		Gen.	1.04	18.0	30.5	19.8
		Trn.	0.214	2.88	21.1	18.9
NG	ST	Min.	0.580	28.6	7.8[illegible]	1.89
		Tsp.	0.234	3.21	8.47	6.06

Fuel	Tech.	SS	Indicator			
			I	AC	VA	CVA
NG	ST	Gen.	1.04	13.6	3.87	-6.81
		Trn.	0.0113	0.273	21.1	21.0
	OCGT	Min.	0.737	38.8	10.3	2.75
		Tsp.	0.294	4.00	11.6	8.61
		Gen.	0.500	7.31	-7.16	-12.3
		Trn.	0.0113	0.273	21.1	21.0
	CCGT	Min.	0.437	20.0	5.66	1.17
		Tsp.	0.179	2.49	5.83	3.99
		Gen.	0.680	11.9	13.2	6.19
		Trn.	0.0113	0.273	21.1	21.0
LNG	ST	Min.	0.647	10.2	1.04	-5.61
		Tsp.	2.04	52.0	39.6	18.6
		Gen.	1.04	13.6	4.29	-6.39
		Trn.	0.0113	0.273	15.1	14.9
	OCGT	Min.	0.817	13.6	1.51	-6.89
		Tsp.	2.67	63.0	59.4	32.0
		Gen.	0.500	7.31	-20	-25.1
		Trn.	0.0113	0.273	15.1	14.9
	CCGT	Min.	0.492	7.35	0.666	-4.39
		Tsp.	1.52	42.0	23.5	7.90
		Gen.	0.680	11.9	24.7	17.8
		Trn.	0.0113	0.273	15.1	14.9

Table of social indicator subsystem contributions(ED and EI = direct and indirect employment (10^6 x employees), LTI = lost time injuries (10^7 x LTI), and Fatal = fatalities (10^9 x fatalities), all per MWh of electricity delivered).

Fuel	Tech.	SS	Indicator			
			ED	EI	LTI	Fatal
BlC	ST	Min.	38.8	289	44.2	7.02
		Tsp.	12.4	35.8	4.77	2.42
		Gen.	27.1	116	2.72	0
		Trn.	1.86	7.97	0.128	0.72
	IGCC	Min.	21.8	163	24.8	3.94
		Tsp.	6.98	20.1	2.68	1.36
		Gen.	27.1	116	2.72	0
		Trn.	1.31	5.61	0.0901	0.507
BlCE	ST	Min.	57.1	426	65	10.3
		Tsp.	47.9	188	17.5	3.78

Fuel	Tech.	SS	Indicator: ED	EI	LTI	Fatal
BICE	ST	Gen.	27.1	116	2.72	0
		Trn.	1.31	5.61	0.0901	0.507
	IGCC	Min.	32.1	239	36.5	5.81
		Tsp.	26.9	105	9.84	2.12
		Gen.	27.1	116	2.72	0
		Trn.	1.31	5.61	0.0901	0.507
BrC	ST	Min.	16.8	125	0	0
		Tsp.	0	0	0	0
		Gen.	18.2	77.8	3.87	0
		Trn.	2.03	8.68	0.139	0.785
	IGCC	Min.	8.67	64.7	0	0
		Tsp.	0	0	0	0
		Gen.	18.2	77.8	2.97	0
		Trn.	2.03	8.68	0.139	0.785
NG	ST	Min.	38	283	9.38	2.45
		Tsp.	6.12	30.6	0.38	1.44
		Gen.	7.89	33.7	0.0108	0
		Trn.	0.109	0.467	7.50×10^{-3}	0.0422
	OCGT	Min.	51.7	386	12.8	3.33
		Tsp.	6.12	41.6	0.38	1.44
		Gen.	3.81	16.3	5.22×10^{-3}	0
		Trn.	0.109	0.467	7.50×10^{-3}	0.0422
	CCGT	Min.	26.4	197	6.53	1.7
		Tsp.	6.12	21.3	0.38	1.44
		Gen.	9.56	40.9	0.0131	0
		Trn.	0.109	0.467	7.50×10^{-3}	0.0422
LNG	ST	Min.	34.1	254	8.42	2.2
		Tsp.	6.15	22.5	0.649	0.629
		Gen.	7.89	33.7	0.0108	0
		Trn.	0.109	0.467	7.50×10^{-3}	0.0422
	OCGT	Min.	46.4	346	11.5	2.99
		Tsp.	8.34	30.7	0.881	0.847
		Gen.	3.81	16.3	5.22×10^{-3}	0
		Trn.	0.109	0.467	7.50×10^{-3}	0.0422
	CCGT	Min.	23.7	177	5.86	1.53
		Tsp.	4.31	15.7	0.454	0.445
		Gen.	9.56	40.9	0.0131	0
		Trn.	0.109	0.467	7.50×10^{-3}	0.0422

A3.3 NORMALISED INDICATORS

Table of normalised environmental indicators. Units all (unit of impact per MWh of electricity delivered) per (unit of impact in Australia per annum)).

Fuel	Tech	Indicator: CC	AD	EU	PS	SW	RD A	RD W	EN	EX
Unit of Impact		kg CO_{2-eq}	kg SO_{2-eq}	kg $PO_4^{3-}{}_{-eq}$	kg C_2H_{4-eq}	kg	kg Sb_{eq}		GJ	
Magnitude		10^{-9}								
BIC	ST	2.22	1.93	1.27	0.318	4.12	0.0192	1.31	2.34	1.56
	IGCC	1.43	0.0493	0.0758	0.0195	2.97	0.0134	0.773	1.36	0.941
BICE	ST	2.33	2.12	1.33	0.355	14.6	0.142	1.98	3.54	2.35
	IGCC	1.49	0.167	0.171	0.0463	8.82	0.0778	1.14	2.02	1.41
BrC	ST	2.54	0.904	0.635	0.150	1.03	4.58×10^{-3}	2.05	2.89	1.41
	IGCC	1.57	0.694	0.0709	0.106	0.644	6.05×10^{-3}	1.10	1.54	0.78
NG	ST	1.52	0.272	0.686	0.160	1.01×10^{-3}	0.137	1.16	1.43	1.36
	OCGT	1.77	0.424	1.07	0.231	1.33×10^{-3}	0.188	1.55	1.92	1.81
	CCGT	0.959	0.120	0.290	0.0994	6.98×10^{-4}	0.0986	0.814	1.00	0.955
LNG	ST	1.84	0.417	0.968	0.374	3.35×10^{-3}	0.274	1.34	1.69	1.57
	OCGT	2.21	0.618	1.45	0.517	4.47×10^{-3}	0.371	1.80	2.26	2.10
	CCGT	1.19	0.221	0.488	0.249	2.34×10^{-3}	0.194	0.941	1.19	1.10

Table of normalised economic and social indicators. Units all (unit of impact per MWh of electricity delivered) per (unit of impact in Australia per annum)).

Fuel	Technology	Indicator: I	AC	VA	CVA	ED	EI	LTI	Fatal
Unit of Impact		\$				Employees		LTI	fatalities
Magnitude		10^{-8}	10^{-11}	10^{-10}				10^{-11}	
BIC	ST	10.0	6.26	2.52	0.745	0.899	5.03	3.35	2.73
	IGCC	6.03	3.78	2.98	2.44	0.641	3.41	1.96	1.56
BICE	ST	9.78	7.42	4.36	3.32	1.50	8.24	5.52	3.93
	IGCC	9.10	5.73	4.70	3.97	0.979	5.23	3.18	2.27
BrC	ST	9.81	4.34	3.38	1.98	0.415	2.37	0.259	0.211
	IGCC	5.59	3.02	3.24	2.91	0.324	1.69	0.201	0.211
NG	ST	5.75	4.27	2.44	1.78	0.584	3.9	0.633	1.05
	OCGT	4.75	4.72	2.12	1.61	0.692	4.98	0.852	1.29
	CCGT	4.03	3.24	2.7	2.60	0.474	2.91	0.449	0.855
LNG	ST	11.5	7.12	3.54	1.73	0.541	3.49	0.588	0.77
	OCGT	12.3	7.87	3.30	1.20	0.658	4.41	0.800	1.04
	CCGT	8.33	5.76	3.78	2.91	0.423	2.63	0.41	0.542

NOMENCLATURE

Nomenclature

Symbol	Explanation
λ_s	Equivalent life of subsystem s (system life, n, divided by life of subsystem, s)
ω	Exponent for power law estimates of O&M
ψ	Exponent for power law estimates of I
A	Pre-factor for power law estimates of I
AC	Annualised Costs (economic indicator), usually includes O&M, C_R, and F
AD	Acidification (environmental indicator)
ADP	Abiotic Depletion Potential; measure of abiotic depletion.
AP	Acidification Potential; measurement of acidification.
Ass.	Assumed
AUD	Currency of Australia (Australian Dollars).
Aust.	Australia
B	Pre-factor for power law estimates of O&M
BlC	Black coal (domestic quality black coal transported wholly within Australia)
BlCE	Export quality black coal (transported to Japan)
BrC	Brown coal
$C_{x,y}$	ADP parameter: consumption of substance x in region y for 1 year
C	EVA method: cost of capital
$C_2H_{4\text{-eq}}$	Ethylene equivalents; units of photochemical smog formation
CA	EVA method: capital expenditure in calculation year
CC	Climate Change (environmental indicator)
CCGT	Combined-Cycle Gas Turbine (Combustion Technology)*
$CF_{x,y}$	Factor representing the relative impact of substance x to the reference substance for LCA impact category y
CH_4	Methane
CML	Centre of Environmental Studies, Leiden (Netherlands)
CO	Carbon monoxide
CO_2	Carbon Dioxide
$CO_{2\text{-eq}}$	Carbon Dioxide equivalents; units of climate change.
Conv	Conveyor
C_R	NPV Method: annual capital investment recovery cost
CVA	Capital value added (economic indicator)
Data Ref.	Data reference number for Appendix 3
ED	Employment (social indicator method)
EDP	Energy or exergy depletion potential
EI	Indirect employment (social indicator method)
EIA	Environmental Impact Assessment
EM	Employment method: employment multiplier derived from input-output tables
EN	Energy depletion (environmental indicator method)
EP	Eutrophication Potential; measure of eutrophication.
ET	Eco-toxicity (environmental indicator)
EU	Eutrophication (environmental indicator)

* See 'Glossary' for further descriptions.

Symbol	Explanation
EVA	Economic Value Added (economic indicator method)
EX	Exergy depletion (environmental indicator method)
F	Economic Methods: Costs for the main fuel consumed
Fatal	Fatalities indicator
GBP	Currency of Great Britain (British Pounds).
Gen.	Electricity generation subsystem
GJ	10^9 Joule; ISO units of energy
GWh	10^9 Watts; units of energy for electricity
GWhpa	GWh per annum
GWP	Global Warming Potential; measure of climate change.
H_2S	Hydrogen sulphide
HHV	High Heating Value
HT	Human toxicity (environmental indicator)
i	Interest rate or amortisation factor (%).
I	Uncertainty assessment parameter for Kennedy et al. (1996) method
I	Investment or capital cost (economic indicator method) Capital requirements (economic indicator)
ICS	Characterised score for an LCA impact category
IGCC	Integrated Coal Gasification Combined-Cycle (Combustion Technology)*
I_R	Relative capital cost (economic indicator)
IRR	Internal Rate of Return (economic indicator method)
ISO	International Organisation for Standardisation
kg	ISO standard unit of mass
km	10^3 metres
kt	10^3 metric tonnes
L	VA Method: costs of labour (i.e. salaries and wages)
L	Distance traversed by transport or transmission subsystem.
LCA	Life Cycle Analysis or Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Analysis or Life Cycle Inventory Assessment
LHV	Low Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LTI	Lost time injuries; injuries for which cause an employee to be absent from work for more than one day.
LTIF	Lost time injury frequency; LTI per 10^6 WH
m_x	Mass rate (kg per unit) of substance or flow x
MES	VA Method: cost of material, energy and services.
Min.	Fuel mining subsystem
Mt	10^6 metric tonnes
Mtpa	Mt per annum.
MW	10^6 Watts; units of capacity for electricity
MWh	10^6 Watt-hours; units of energy for electricity
n	Life of system (years)
N	Life of project (years)
N_2O	Dinitrogen oxide (a greenhouse gas)
NG	Natural gas transported by pipeline wholly within Australia
NMVOC	Volatile organic compound
NO_2	Nitrogen dioxide

Symbol	Explanation
NOPAT	EVA method: net operating profit before tax
NO_x	Nitrogen Oxides
NPC	Net Present Cost (economic indicator method)
NPV	Net Present Value (economic indicator method)
NSW	Australian state of New South Wales
O	Operating costs
O&M	Operating and maintenance costs (O&M = O – (Capital + F))
OCGT	Open-Cycle Gas Turbine (Combustion Technology)* or Gas Turbine
OEI	Overall environmental index (weighted sum of environmental indicators)
P	NPV Methods: actual production of desired product(s) VA Method: purchased materials, energy and service.
$PO_{4\text{-eq}}$	Phosphate equivalents; units of eutrophication.
POCP	Photo-Oxidant Creation Potential; measure of photochemical smog formation
PM	Particulates (environmental indicator method)
PS	Photochemical smog (environmental indicator)
Q	Capacity of subsystem, i.e. maximum production of desired product(s).
Qld.	Australian state of Queensland.
R	VA Method: cost of raw material purchases.
$R_{x,y}$	ADP parameter: resource of substance x in region y
Rail1, Rail2	Refers to the domestic and foreign rail transport legs in the BICE transport subsystem.
RD A	Resource depletion, Australian reference region (environmental indicator method)
RD A	Resource depletion, world reference region (environmental indicator method)
Ref.	Data reference number for Appendix 3
S	VA Methods: sales revenue
$Sb_{\text{-eq}}$	Antimony equivalents; units of abiotic depletion.
SD	Standard deviation
SG	Specific gravity: ratio of substance density to water (liquid) or air (gas)
SO_2	Sulphur dioxide
$SO_{2\text{-eq}}$	Sulphur dioxide equivalents; units of acidification potential.
ST	Steam turbine*
SW	Solid waste (environmental indicator method)
Sys.	System
t	ISO metric tonnes
Trm.	Electricity transmission subsystem
Tsp.	Fuel transport subsystem
U.K.	United Kingdom or Great Britain
USD	Currency of the U.S.A. (U.S. Dollars)
VA	Value added (economic indicator method)
Vic.	Australian state of Victoria.
VOC	See NMVOC
WD	Water consumption (environmental indicator method)
WF	Weighting factors to produce an OEI
WH	Work hours; hours of employee work time.
WP	LTIF method: worker productivity (hours worked per annum per employee)
x	Uncertainty assessment parameter for Kennedy et al. (1996) method

Table of Systems (technology descriptions in Nomenclature and Glossary).

Systems	Explanation
BIC-ST	Fuel: BIC (domestic quality black coal transported wholly within Australia) Technology: ST (steam turbine)
BIC-IGCC	Fuel: BIC Technology: IGCC (integrated gasification with combined cycle gas turbine)
BICE-ST	Fuel: BICE (export quality black coal transported to Japan) Technology: ST
BICE-IGCC	Fuel: BICE Technology: IGCC
BrC-ST	Fuel: BrC (brown coal transported wholly within Australia) Technology: ST
BrC-IGCC	Fuel: BrC Technology:IGCC
NG-ST	Fuel: NG (natural gas transported by pipeline wholly within Australia) Technology: ST
NG-OCGT	Fuel: NG Technology: OCGT (open cycle gas turbine)
NG-CCGT	Fuel: NG Technology: CCGT (combined cycle gas turbine)
LNG-ST	Fuel: LNG (liquefied natural gas transported to Japan) Technology: ST
LNG-OCGT	Fuel: LNG Technology: OCGT
LNG-CCGT	Fuel: LNG Technology: CCGT

GLOSSARY

Acidification – an **LCA impact category** and **indicator** of **sustainability** (AD) associated with the fall in pH due to the rise in acidifying gases in the atmosphere. Major acidifying gases are NO_x and SO_x, which when reacted with water become HNO_2, HNO_3, and H_2SO_4. These acids mix with falling rain, and among other things cause the discoloration and dissolution of marble structures and a fall in the pH (alkalinity) of lakes.

allocation – the act of proportionally distributing the responsibility for resource consumption, emissions and waste streams from processes in the life cycle. Is used when more than one (useful) product is generated from a **subsystem**.

Annualised Costs – an economic **indicator** of **sustainability** (AC) representing wealth generation including both **capital** and **operating** costs. The **capital costs** are annualised, which is a common method of depreciation when estimating costs for electricity generation systems. Annualisation modifies the discounted annual capital contributions so that they have a constant value (see Figure 3.3.1, Chapter 3)

artesian water – water which exists below the surface in water bearing rocks, sands and gravels. An aquifer is a discrete source layer of artesian water.

ash – non-combustible fraction of coal, which is removed as a solid. Fly-ash is the fraction of ash which is too small to settle in the boiler and is collected by a particulate removal device, i.e. electrostatic precipitator or baghouse. Bottom ash is the fraction of ash that settles in the boiler. Removal is by mechanical, pneumatic (air) or hydraulic (water) means.

black coal – coal which has a higher energy content that 17 MJ per kg. Includes coal of the anthracite, bituminous, and sub-bituminous classifications. This coal has an export value, and contributes significantly to Australian exports.

brown coal – coal which has an energy content lower than 17 MJ per kg. Includes coals of the lignite, and some sub-bituminous (C) classifications. Australian brown coals are characterised by their very high moisture content (50-66 % of their mass), and low energy contents (8-10 MJ per kg), which limits their export value.

capital costs – that fraction of costs which can be considered as once off, and occurs before the operation of the facility, i.e. construction costs. It does not include costs for the maintenance of capital after the facility has begun operating. These and other costs accrued continuously through the life of the plant are considered **operating**

costs.

Capital Inclusive Value Added – an economic **indicator** of **sustainability** (CVA) representing wealth generation. CVA is the difference between **value added** (VA) and annualised capital costs (C_R) (see **annualised costs**).

characterisation – the process of quantifying the environmental impact. Uses factors representing the relative magnitude of the impact caused by one substance to a reference substance, i.e. methane (CH_4) is 11 times more effective than carbon dioxide (CO_2) in **Climate Change**, thus 1 tonne CH_4 is characterised as 11 tonnes of CO_2. These conversion factors are **equivalency factors** (CF).

classification – the act of identifying the appropriate **impact category** to which **inventory data** belongs.

Climate Change – an **impact category** and **indicator** of **sustainability** (CC) associated with the output (or emission) of **greenhouse gases**, for example, CO_2, CH_4, CFC's, etc. Climate Change is, under this definition, the change in climate due to the rise in global temperature caused by **greenhouse gases**.

coke breeze – fuel consisting of fines (small particles) generated during the process of making coke from **black coal**.

Combined Cycle Gas Turbine (CCGT) – a generation technology used for gaseous fuels (such as natural gas, processing and refinery waste gases, and manufactured gases (e.g. gasified coal or biomass)) or light fuel oils. The key features of a CCGT are the gas turbine, heat recovery steam generator (HRSG), and the steam turbine (Figure 4.2.8, Chapter 4). It is the combined use of a gas and steam turbine, which allows such systems to produce efficiencies of over 50 %.

criteria – (in sustainability assessment) a target score for an indicator. The setting of criterion is a value choice, and thus criteria have no scientific basis.

draglines – mining machinery used in black coal mining. It is a crane like machine with a large shovel rather than a hook. This design gives a large operational range.

dredger – mining machinery used in brown coal mining. There are two designs in operation in Australia, the bucket-wheel and the ladder types. Both operate continuously and dump directly onto a conveyor belt system.

Eco Toxicity – an **impact category** and **indicator** of **sustainability** (ET) associated with the emission of substances that are harmful to animals and plants. This category excludes humans (see **Human Toxicity**).

electricity generation efficiency – a measure of the effectiveness of energy conversion from fuel energy to electricity in the generation subsystem. It is the ratio of the energy exported as electricity over the energy entering as fuel. This thesis uses a higher heating value (HHV) basis for all energy efficiencies.

eqivalency factor (CF) – the value used to convert one substances emission value (say kg substance) to that of the impact **category indicator** (say kg indicator).

Eutrophication – an **impact category** and **indicator** of **sustainability** (EU) associated with the rise in the concentration of nutrients in the environment. Compounds high in nitrogen (N) or phosphorus (P), such as those found in fertilisers, are the primary cause. Consequences of eutrophication are increased algae and other weed growth, which, in waterways, causes a drop in water oxygen content and thus a drop in the numbers of aquatic animals. Also known as 'nutrification'.

Extraction of Biotic Resources – an **impact category** associated with the consumption of animal and plant resources. It considers resources regenerated through both direct human activity (i.e. farming) and natural processes (i.e. hunting, fishing, forestry, etc.).

fuel costs – costs accrued through the regular purchase of fuels throughout the life of the plant are called **fuel costs**.

fugitive emissions – emissions of a substance which is not intentional or accidental, i.e. petroleum or natural gas from a leaking pipeline.

gasification – the conversion of coal to a low-energy content gas through partial oxidation, usually in the presence of steam (i.e. coal + oxygen + steam ⇒ carbon monoxide + hydrogen + methane + carbon dioxide).

greenhouse gas – any gas which remains in the atmosphere for a sufficient period to absorb energy radiating from the surface of the earth, and thus increase the temperature of the atmosphere (global warming or **climate change**).

Human Toxicity – an **impact category** and **indicator** of **sustainability** (HT) associated with the emission of substances that are harmful to humans.

impact category – a class representing environmental impacts of concern into which LCI results may be assigned (ISO term).

indicator (of sustainability) – a measure representing an environmental, economic or social impact of concern.

integrated gasification combined cycle (IGCC) – a generation technology which converts a solid fuel to gas (**gasification**), cleans the product gas, and provides it to a combined cycle system (Figure 4.2.4, Chapter 4). Gasification in an IGCC is usually in a fluidised bed gasifier. There are many IGCC designs.

inter-generational equity – a theoretical situation in which all persons, no matter their location in time, have equal opportunity to live with a high level of well-being, and to access financial and natural resources. The context is usually equal to or greater, rather than equal to (as the strict definition would suggest).

intra-generational equity – a theoretical situation in which all persons, no matter their present location, have equal opportunity to live with a high level of well-being, and to access financial and natural resources. In the current situation persons in industrialised countries have greater access than persons in developing countries, as they have generally have greater financial power.

Land Use – an **impact category** associated with the change in how the effected land is used. For example, the building of a plant in a virgin forest involves a change in land use. However, the building of a plant on an industrial site, which previously contained a similar plant, involves no change in land use.

Life Cycle Analysis (LCA) – Life Cycle Assessment (or LCA) is a recently developed method of environmental analysis for quantifying the environmental effect of any product, process or service over its entire life cycle, from raw material acquisition to ultimate disposal.

natural gas – petroleum gas, high in methane (up to 96 %). Production is often coincidental with crude oil and other petroleum products. Liquefaction of natural gas (LNG) is common for ocean transport.

NMVOC – Non-methane volatile organic compounds. Category of emissions to air, including all organic compounds, except methane, that are likely to evaporate, or are present in a gas stream.

normalisation – the conversion of **impact category** indicator and **indicator** of **sustainability** values from their absolute value to a dimensionless number representative of its relative contribution to a given region's impacts. This involves dividing the absolute value by the total impact generated by the region.

Open-Cycle Gas Turbine – a generation technology used for gaseous fuels (such as natural gas) and light fuel oils. The gas turbine system consists of a compressor, combustion chamber, turbine, generator and associated auxiliary equipment (Figure

4.2.7, Chapter 4).

operating costs – that fraction of costs which is accrued continuously through the life of the facility. It also includes the cost maintaining capital items during operation. O&M is a limited set of these costs, excluding loan and interest repayments and costs of products produced in earlier subsystems (i.e. the black coal used in the generation system). See also **capital costs**.

overburden – mining term for undesirable material which lies above a body of a particular desirable ore body. Usually used when the ore body is horizontal or near horizontal to the surface.

Photo-oxidant Formation – an **impact category** and **indicator** of **sustainability** (PS) associated with the formation of a brown cloud of pollutants, which usually occurs in urban areas. Major precursors are NO_x, VOC's, and particulates, which are released through incomplete combustion in cars, and other combustion systems, and **fugitive emission** sources.

renewables – energy sources that are regenerated naturally, or can be regenerated through the action of man, within the short time spans required for significant consumption. These include sunlight, wind, water (river and sea/wave), and biomass.

Resource Depletion – an **impact category** and **indicator** of **sustainability** (RD) associated with the use of mineral and energy resources. It considers the reduced resources caused through mining, and oil and gas production. It does not consider the energy use and emissions caused through these activities. Also known as 'Extraction of Abiotic Resources'.

sphere – an category of sustainability. Refers to the environment, economy or social classifications in sustainability.

spoil piles – the material produced from a coal mine that is too high in non-coal material to be utilised. It is generally stockpiled near the mine site and is prone to natural decomposition and spontaneous combustion.

Steam Turbine (ST) – a generation technology used for solid fuels, where the solid fuel is broken or pulverised into small particles and carried with the combustion air to the burner mouth. Most commonly the system is used for coal, however any solid fuel can be used, i.e. bagasse, municipal waste, etc. The system consists of many sections, including fuel preparation, boiler, steam turbine, condenser, fans, flue gas

cleanup, stack, and ash handling plant (see Figure 4.2.3, Chapter 4). This system can also consume gas (i.e. natural gas) and liquid (i.e. oils) fuels.

Stratospheric Ozone Depletion – an **impact category** associated with the decrease in ozone (O_3) in the Ozone Layer. The Ozone Layer provides the planet shelter from harmful ultra-violet (UV) radiation, which are produced by the sun. These UV rays have been proven as the major cause of skin cancers in humans and animals.

subsystem – a subsystem is a well defined processing step, such as mining, transport and generation in coal generation systems, or production, processing, transmission, and generation in natural gas generation systems. Subsystems link together without crossover.

Sustainable Development – the act of improving the harmful effects of present products, processes, and services, on the environment, economy, and social welfare of the world. It is also, the act of progressing, through advancement, towards the ideal state of **sustainability**. In this thesis, **sustainability** and **sustainable development** have identical meanings in line with common usage.

Sustainability – theoretical end state in which further **sustainable development** is no longer necessary (i.e. harmful effects of humans balanced by positive natural and human responses). The ideal state, meeting all needs of the present population, without reducing the probability of future generation's having similar or better welfare.

system – in the context of a **Life Cycle Assessment (LCA)** or **Sustainability** Assessment the system is the group of **subsystems** which adequately describe the life cycle of the product under study.

system boundary – describes the boundary between what is considered to be a part of the **system** and the general environment. All substances crossing this boundary should be raw materials, which have yet to be processed, or emissions, which will not undergo any further processing.

Value Added – an economic **indicator** of **sustainability** (VA) representing wealth generation. VA is the difference between the sales revenue and the purchases of materials, energy and services for a given **system**.

washery rejects – coal containing material which, after the washing process (where high ash and low ash coal are separated), contains too high an ash content for sale.

water (high quality) and **water (low quality)** – high and low quality water correspond to municipal drinking water ('tap water') and surface waters from rivers, lakes, reservoirs, estuaries and seas.

Water Consumption – an **impact category** and **indicator of sustainability** (WD) associated with the use of water resources and the increased competition, between other users (human or otherwise), this may cause. This includes the use of surface, sea, ground and artesian water.

weighting – an optional step in the LCIA which involves the combination of individual **impact category** values into a single index.

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ERRATA and ADDENDUM (CONTINUED)

pg. 64, Equation 3.2.2: 'Exergy Destruction' replaces 'Exergy Depletion' and 'Energy Depletion' replaces 'Energy Content'. Add footnote: 'For more details on the exergy destruction method see Ayres, R. U., Martinás, K. and Ayres, L. W. (1996), *Eco-thermodynamics. Exergy and life cycle analysis*, Working Paper (96/04/EPS), INSEAD, Fontainbleau, France.

pg. 65, Equation 3.2.3 note: '…system (e.g. kg…' replaces '…system (kg…' for both occasions and '…substance c (e.g. kg…' replaces '…substance c kg…'

pg. 73, para. 2: '…where one stream contributes twice as much as the other to environmental impact.' replaces 'and contributions of 33% and 67% of the environmental impact result respectively.'

pg. 83, para. 1: '…have identical revenue.' replaces '…have identical positive cash flow.'

pg. 83, footnote: 'i = real interest rate' replaces 'i = real inflation rate'

pg. 87, para. 1: 'For example, one project (A) …' replaces 'For example, a one project (A) …' and '…, such as interest and loan payments.' replaces '…, such as interest and load payments.'

pg. 94, para. 1: '… without contributing to the LTI indicator.' replaces '… without contributing the LTI indicator'. The following replaces the paragraph beginning 'Of the indicator methods, …':

'Of the indicator methods, only the LCA method (Section 3.2.3) was originally developed to have boundaries with a 'life-cycle' perspective. This section examines whether the operations that allow the LCA method to combine data from subsystems of a 'life-cycle' perspective system to obtain and analyse system scores may also apply to the economic and social indicators of sustainability.'

pg. 99, para. 2: '…before data collection begins.' replaces 'before data collection.'

pg. 100, para. 1: 'estimate the effect' replaces 'estimate the affect' and **para. 3** '… and assisting duplication of the results of the study…' replaces '… and assisting duplication the results of the study…'. **Para. 5:** The sentences beginning from 'Consequently, the…' are replaced by: 'Consequently, the accuracy of data from Australian electricity generation systems is greater than from foreign and different systems. Data from these later systems is only used when data from Australian electricity generation systems is lacking. Average values are used whenever multiple sources of data are available. …'

pg. 102, caption: '(dashed boundary = all impacts, dotted boundary = economic impacts only).' replaces '(grey = all impacts, spotted = economic impacts only).'

pg. 105, figure: replacement of figure with Figure B.

pg. 107, para. 1: After '(Data Ref. C1).' is added 'The composition of black coal is given in Figure 4.3.4.', **para. 2:** after 'during normal operation.' is added 'Often mined-out areas are rehabilitated during the mining of new areas.' and **para. 4:** after '…not include overburden.' is added 'Overburden is only a solid waste if it accumulates rather than being re-used as fill.'

pg. 108, Table 4.3.3 caption: Added 'The equations refer to a power law equation using the A and ψ parameters (see Equation 3.3.6, Chapter 3).'

pg. 108, Table 4.3.4 caption: Added 'The equations refer to a power law equation using the B and ω parameters (see Equation 3.3.10, Chapter 3).'

pg. 123, figure caption: Added 'Scaled interval is 0 to 60 m.'

pg. 156, para. 3: 'all methods shown in Section 3.2.3.7 (Chapter 3).' replaces 'methods developed for use in LCA, all appearing in Section 3.2.3.7 (Chapter 3).', 'and the climate change, acidification and world resource depletion indicators.' is added to sentence beginning 'Time and resource constraints limit…' and '(Finnveden and Lindfors (1998))' is added after ''rules of thumb''.

pg. 157, para. 2: '…assumes that the destination is Japan.' replaces '…assumes that the destination in Japan.'

pg. 169, para. 2: '(see Section 4.4.2, Chapter 4)' is added after 'the CC, AD and RD W indicators'

pg. 175, para. 1: 'show the major effects' replaces 'show the major affects'

pg. 182, para. 2: '10^{-10}-10^{-9}' and '10^{-11}' replace '10^{10}-10^{9}' and '10^{11}'

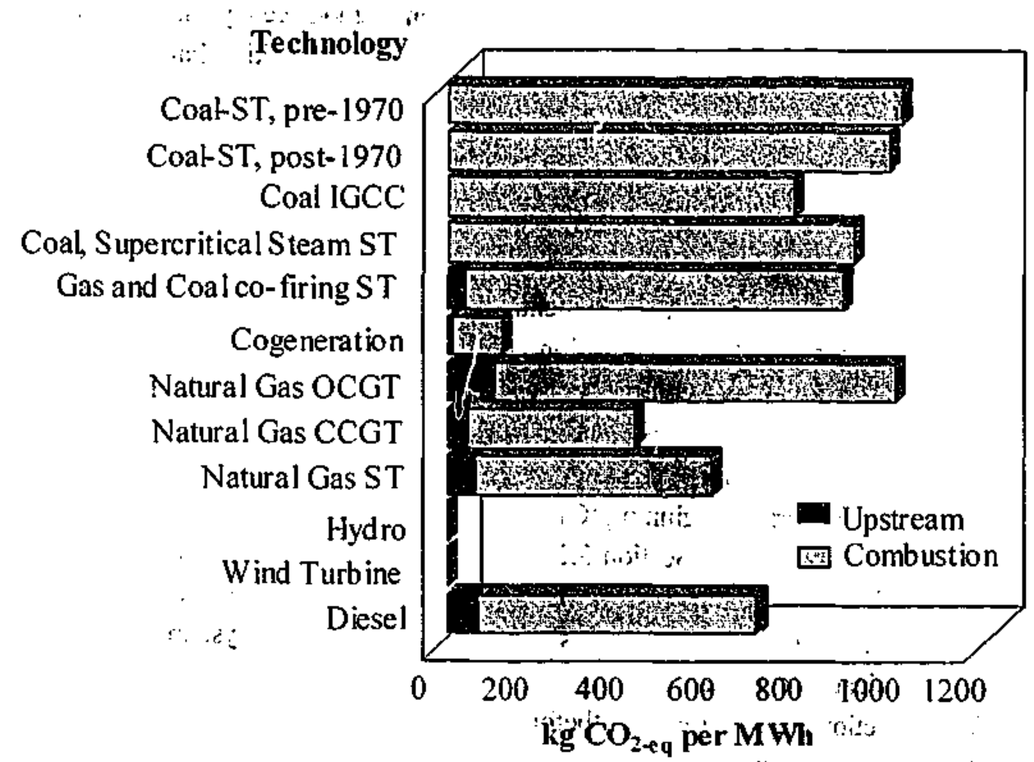

Figure A

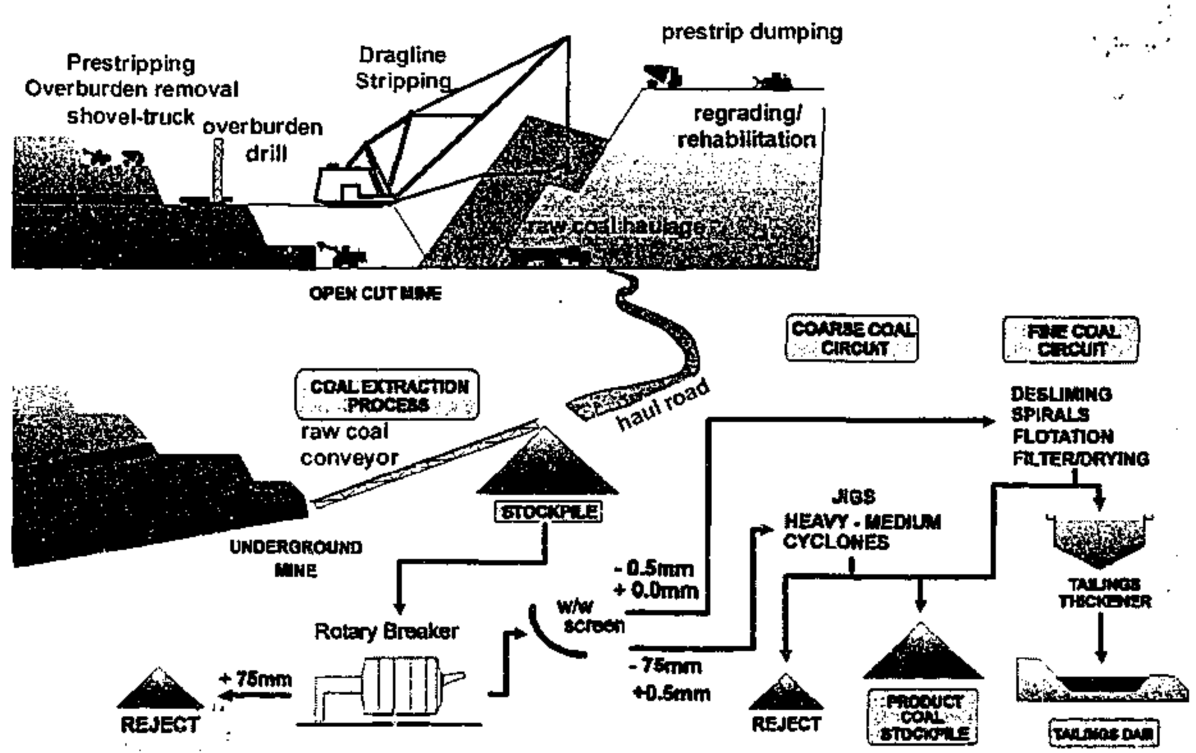

Figure B