Strategic Sustainable Development for the Stationary Power Sector:

Is Carbon Capture and Storage a Strategic Investment for the Future?

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Abstract:

An examination of the stationary power sector is performed using The Natural Step framework and Sustainability Principles (SP), in order to aid decision makers in developing policy to balance energy needs while reducing carbon dioxide (CO_2) emissions in order to address climate change.

Carbon capture and storage (CCS) is evaluated for its sustainability aspects, and is found to be a potentially sustainable approach which can be a bridging technology to a more sustainable energy mix, as well as a remediation technology which can remove CO_2 from the atmosphere when utilized in combination with biomass fuel.

Initial actions for restructuring the stationary power sector should emphasise demand reduction and efficiency efforts, followed by switching to renewable energy sources. If the first two strategies can not provide sufficient CO_2 reductions, then investments in CCS technology may be an appropriate choice. CCS with coal-fired power can be a means to decouple CO_2 emissions from fossil fuel use, but other SP violations associated with coal use must also be fully addressed before this strategy can be considered a truly sustainable option.

Keywords:

Carbon sequestration, Carbon capture and storage, Stationary power, Policy, Strategic sustainable development, Sustainability principles

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Executive Summary

The purpose of this report is to first understand society's interaction with the biogeochemical carbon cycle as a result of energy consumption, and then to consider the potential role of fossil fuels in the transition to a sustainable energy future, utilizing *The Natural Step's* sustainability principles and backcasting methodology. Carbon Capture and Storage (CCS) is analyzed in detail to determine the extent to which it might be successful strategy. Finally, the intent is to create a framework or mental model for policy makers in government to utilize to analyse the wide range of energy and CCS options which can meet the energy needs of a growing, industrializing population. Policy options are outlined, but generalized decisions are not recommended due to the need for local and/or regional input, which can vary considerably The following research questions provide the basis for the investigation:

- Can point source carbon, notwithstanding fuel source, be sequestered in a sustainable manner?
- Will investments in fossil fuel based CCS be a strategic step towards a sustainable stationary power sector?
- What should governmental policy-makers take into consideration in order to develop sustainable strategies within the stationary power sector?

Methods include literature review, expert interviews, system dynamics, and mathematical modeling. The results of this study indicate that point source carbon can be captured and stored in a sustainable manner. The preferred CCS technologies are gas separating membranes and sub-ocean geological reservoirs.

This report shows that CCS is a flexible platform, because if biomass fuel is used rather than coal, it enables for the first time, an effective approach to removing CO_2 from the atmosphere. This is possible because the biomass incorporated CO_2 from the atmosphere during its growth through photosynthesis, and when CCS is implemented in conjunction with biomass, the CO_2 that is re-released through combustion will be permanently stored underground. The importance of such a weapon in our arsenal to combat CO_2 emissions and climate change cannot be overstated.

Governmental policy-makers should utilize a systems perspective which can explore the trade-offs and complexity of the power sector. Prioritization of the strategies will be region specific; there is no single answer to the question of which energy technology option to choose. The strategy should also be dynamic and change over time such that initial investments in energy efficiency can provide savings for future investments in a mix of renewable technologies and CCS with fossil fuels during the transition. In order to make meaningful comparisons between technology options, sustainability violations should be quantified by including the externalities to show the overall cost to society in other sectors. This transition will be greatly facilitated by sensible policy which makes CCS the least cost option when penalties such as carbon taxes or caps are in place.

Investments in fossil fuel based CCS can be a strategic step towards a sustainable stationary power sector. It is important to implement this technology because of the large and growing base of coal-fired power plants, and the plentiful supply of coal worldwide.

List of Abbreviations

CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
GWP	Gross World Product
H_2O	Water
IGCC	Integrated Combined Cycle Gasification
LHV	Lower Heating Value
N_2	Nitrogen
NGCC	Natural Gas Combined Cycle
NOx	Nitrogen Oxides
PCC	Pulverized Coal Combustion
PV	Photovoltaic
SOx	Sulphur Oxides
SSD	Strategic Sustainable Development
TNS	The Natural Step
ZET	near-Zero Emissions Technologies

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1 Introduction

Viewing the history of human progress over the past two centuries from the perspective of energy is a fascinating and compelling study. It has been a period of dramatic advances in technology and quality of life, much to the benefit of industrialized societies. With each advance came an increasing reliance on fossil fuels as a primary energy source, and an overall increase in energy intensity of lifestyle. Energy intensity is defined as the amount of energy required to produce one unit of gross domestic product. There are many lifestyle factors that influence energy intensity, including the energy efficiency of buildings and appliances, fuel efficiency of vehicles, distance traveled in vehicles, mass transportation availability, cold or warm climate requiring heating or cooling, and many other factors. About 80% of the world's primary energy supply is from fossil fuels (Figure 1.1**Error! Reference source not found.**) and stationary electric power production is responsible for 37% of the world's CO_2 emissions.

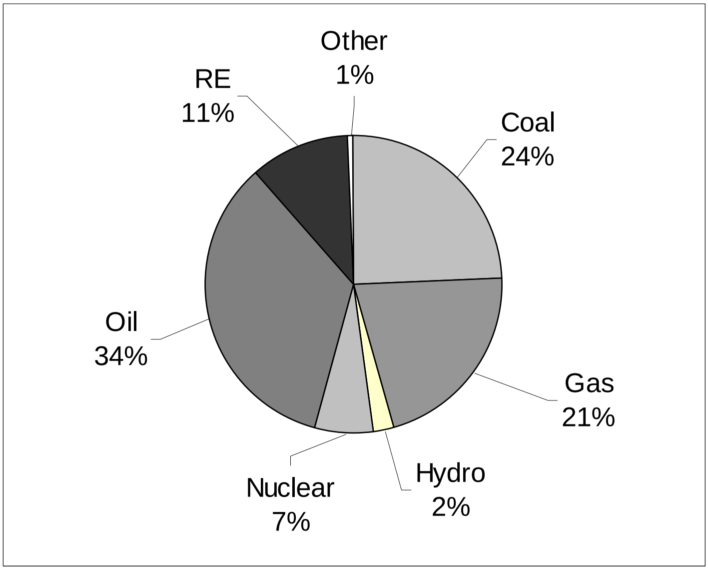

Figure 1.1. World total primary energy supply (IEA 2005a, 8)

The predominant stationary electric power technologies are shown in Figure 1.2. Since coal is responsible for 40% of electricity generation worldwide, it is a large target for reductions in CO_2.

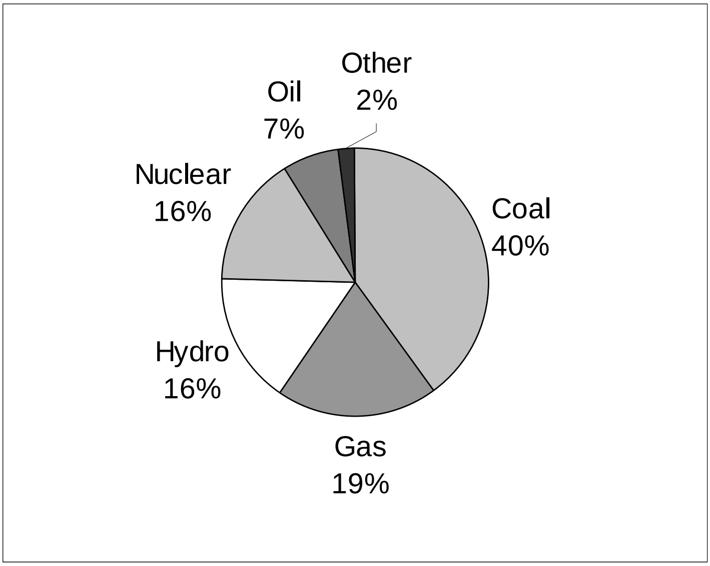

Figure 1.2. 2003 world electricity generation by fuel (IEA 2005a, 26)

While three quarters of the anthropogenic CO_2 released into the atmosphere over the last century has been emitted by the industrialized world, the developing world is now rapidly increasing its fossil fuel consumption as it endeavours to acquire the benefits of a more technologically-advanced society. Countries which have had historically low energy intensities, but with ambitions for rapid development and industrialization in this century include China, with its large population, and India, which is large and growing. The effect of the industrialization of these large "economies in transition" upon both energy consumption and greenhouse gas emissions is significant. Given the strong historical correlation between increasing gross domestic product and higher energy intensities, fossil fuel use and CO_2 emissions are projected to rise significantly unless a commitment is made to sustainable development (WRI 2002).

In some societies, positive change is occurring however, as a result of two key mega-trends that are driving policy shifts: climate change and declining fossil fuel availability (which will ultimately have the effect of increasing energy prices). These mega-trend drivers will be elaborated upon in the following sections.

1.1 Climate Change

Within the past two years in particular, significant environmental changes have been observed, with a rapidity and magnitude which have exceeded the predictions of climate models. Polar ice caps and arctic sea ice are thinning. The melt zone in Greenland is expanding, which, in addition to contributing to rising sea levels, decreases salinity in the ocean which could potentially cause the Gulf Stream current to collapse, creating significant cooling on both sides of the Atlantic (Gagosian 2003). Forest composition is shifting radically, with warm climate species such as oak expanding into coniferous zones. Since the 1970s, the number of category four and five hurricanes has increased dramatically, as sea temperatures have raised.

Though it is difficult to make a direct causal link between specific weather events such as Hurricane Katrina and the long-term trend of climate change, simply examining economic losses due to extreme weather events argues for applying the precautionary principle in allocating resources to address this problem, as costs are likely to continue rising. From the 1950's through the 1970's, economic losses due to extreme weather events rarely exceeded $10 billion US dollars (USD) per annum (IPCC 2001a). Since the 1980's there has been a steep increase in losses, and in the past four years alone, extreme weather related annual losses have climbed from $50 billion to nearly $200 billion USD (UNEP 2005). The Stern review on the economics of climate change estimated that the cost of stabilization of CO_2 at 550 ppm by 2050 will cost 1% of global GDP annually. This is significant but the cost of inaction will be even greater, as GDP will be reduced by up to 20% than otherwise expected if no action is taken (Stern 2006).

1.1.1 Biogeochemical Carbon Cycle

At the beginning of the Industrial Revolution, CO_2 was present in the atmosphere at 280 parts per million by volume (ppmv). Since then, more than 3,900 gigatons (Gt) of carbon dioxide have been released into the atmosphere through fossil fuel and biomass combustion, and the depletion of soils (Socolow 2005). In addition to this, the biosphere's ability to naturally absorb carbon has been systematically undermined through physical degradation of natural terrestrial sinks, such as forests and vegetation. Anthropogenic emissions of CO_2 are 6.6 Gt per year, which exceeds absorptive capacity of natural sinks by 3.3 Gt per year (IPCC 2005, 12). As a result, the atmospheric CO_2 concentration was 375 ppmv in 2003 (Blasing and Jones 2005), one-third higher than it has been in the past 650,000 years (Figure 1.3) (Brook 2005).

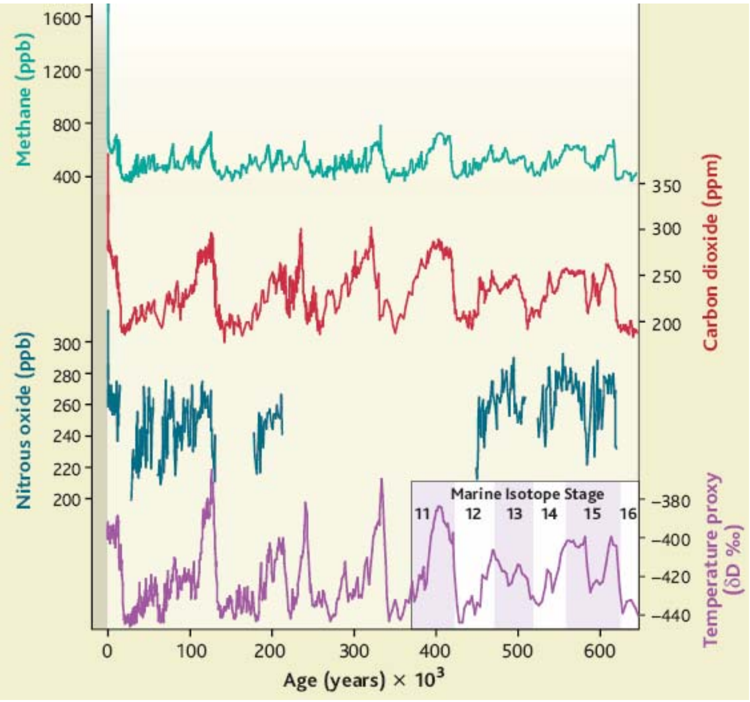

Figure 1.3. The EPICA ice core (Brook 2005)

Carbon dioxide is acknowledged as the primary greenhouse gas (GHG), and there is strong consensus within the scientific community that higher atmospheric CO_2 concentrations are causing increasing climate instability and increasing global mean temperature at a rate faster than the adaptive capacity of the biosphere. Increasing atmospheric CO_2 concentrations are linked to the Greenhouse Effect, which gives rise to increasing global land, air and ocean temperatures. One consequence is a higher level of water vapour in the atmosphere, which when coupled with higher ocean temperatures, gives rise to more violent storms.

Over the past 150 years, there has been an increase in mean global temperature of approximately 0.6°C (IPCC 2001b, 105). Numerous climate models have predicted global mean temperature increases of between 1.5 and 6 °C over the next 100 years (Ibid, 555).

1.2 Fossil Energy

With growing dependence on coal for electricity generation worldwide, it is essential that CO_2 emissions from this source be addressed. Action must be taken to first stabilize, and then ultimately reduce, atmospheric CO_2 levels within an acceptable time frame. Despite concerted actions such as the Kyoto Protocol on climate change, the International Energy Agency predicts that electric power-related CO_2 emissions will increase by 52% by the year 2030 (IEA, 2005b, 79). Electricity generation and heat account for most of the "addressable" CO_2 emissions, comprising about 32% of US GHG emissions (WRI 2005). Because CO_2 emissions from stationary power plants are relatively concentrated (e.g. flue gas is 15% CO_2 by volume, vs. 375 parts per million in the atmosphere), these sources are obvious candidates for abatement efforts, where emissions can be mitigated "upstream" of the atmosphere. Other sources of CO_2, such as most forms transportation are less compatible with abatement technologies, and therefore fuel switching to sustainable fuels must be considered instead.

Even as demand rises for fossil fuels, production rates from key reserves of oil and natural gas are diminishing. Global production of "conventional" or crude oil is expected to peak in 2005 at 1900 billion barrels, while "unconventional" oil sources (heavy, deepwater and polar oil, and gas liquids) are predicted to peak in 2010 (ASPO 2006, 2). Natural gas production has been in decline in North America, which is a strong driver for developing liquefied natural gas imports from the Middle East (EIA

2006a). The cost of natural gas in North America increased by 50% during 2005, which is encouraging fuel switching to cheap coal for stationary power production.

Coal is the most plentiful of the fossil fuels, with an estimated 200 years of supply at current consumption levels[1] (EIA 2004a). In addition, new uses of coal are being commercialized more widely, since it can be converted into diesel or synthetic natural gas through a chemical process known as the "Fischer-Tropsch" process.

These fundamental supply constraints make questionable any large capital investments in rapidly depleting (and increasingly economically unfavourable) primary energy sources. However, short-term energy needs and economic goals are winning out over strategic, long-range planning. To ensure a sustainable energy future, governmental policy makers should consider technology options that will be viable beyond the expiration date of our current suite of fossil fuels.

1.2.1 Carbon Capture and Storage

Since the 1970's, the oil industry has developed methods for separating CO_2 from natural gas and from combustion gases and also developed the capability to inject CO_2 back into underground geological reservoirs. These technologies are collectively known as 'carbon capture and storage' (CCS). CCS encompasses a number of physical and chemical approaches to separate CO_2 from other gases and then store it permanently, securely and in an environmentally benign form. There are multiple chemical, biological and physical approaches from which to choose. From an economic, engineering and scientific perspective, each method has its own set of risks, assumptions, and impacts on biological and economic systems, all of which will be explored in the Results section (Chapter 3). The term 'carbon sequestration' is also widely used, but it is quite broad and encompasses

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[1] Coal is only estimated to last 200 years at *current consumption levels.* Energy (and coal) consumption continues to grow annually. A 2% annual increase could exhaust this supply in 50 years. (Weisz 2004, 50)

both natural sinks (e.g. forests, soil) and the chemical transformation of CO_2 to inert, stable compounds. We have limited the scope of this paper to technologies which can be coupled with large point source emissions within the context of the power generation sector, as a method of decoupling the use fossil fuels from increasing CO_2 concentrations in the atmosphere.

1.3 Research Questions

Given the complexity of the global energy system, it is likely that a combination of approaches and technologies will be required to address the CO_2 challenge. To avoid further catastrophic climate impacts, it will be necessary to stabilize atmospheric CO_2 levels by cutting emissions, even while energy demand increases, and ultimately bring CO_2 levels back towards historical norms. Clearly, significant investments in energy efficiency, renewable energy and alternatives such as nuclear must be carefully considered to balance supply and demand, environment and economy, and meet human needs worldwide. The many stakeholders and interests must be weighed against each other, but the final answers must preserve the earth's ability to support the biosphere and human society. The strategic challenge for decision- and policy-makers is to critically prioritize investments over a short- to mid-term timeframe (5-15 years), in order to mitigate the long-term (20 – 100 years) risks to our planet's climate, and the security and the stability of global society. The solutions must be timely, in order to address the urgency of the situation, and also balance current and future economic repercussions.

To inform policies for a strategic transition towards sustainability within the power sector requires a creation of robust tools and concepts for decision-making. In order to make sustainable choices in such a complex system, it is necessary to take a rigorous and systematic approach. In this thesis, a systems dynamics perspective of society's impact upon the carbon cycle is used to help determine the key relationships and leverage points for impacting the system, and develop a strategic plan for a dynamic energy infrastructure transition.

Utilizing a framework for Strategic Sustainable Development[2] (SSD), the specific purpose of this report is to first understand society's interaction with the biogeochemical carbon cycle, and then to consider the potential role of fossil fuels in the transition to a sustainable energy future. Carbon capture and storage is analyzed in detail to determine the extent to which it might be successful strategy. Finally, the intent is to frame the energy sustainability challenge for policy makers so that they take the appropriate factors into considering in their selection of potential energy generation and CCS technologies that can meet the energy needs of a growing, industrializing population.

The following research questions will provide the basis for the investigation:

1. Can point source carbon, notwithstanding fuel source, be sequestered in a sustainable manner?

2. What should governmental policy-makers take into consideration in order to develop sustainable strategies within the stationary power sector?

3. Will investments in fossil fuel based CCS be a strategic step towards a sustainable stationary power sector?

In addition, several hypotheses were articulated:

- **Hypothesis 1:** that the current major point source power generators are not sustainable
- **Hypothesis 2:** that CCS could play an important role as a sustainable emissions reduction and/or mitigation technology
- **Hypothesis 3:** Renewable power generation technologies have a possibility of being sustainable options
- **Hypothesis 4:** Fossil fuels are firmly entrenched in the power generation sector. Coal especially, is gaining momentum as the cost of natural gas is causing a shift towards dirtier, more CO_2 electrical power

[2] Also known as The Natural Step Framework, further elaborated in Section 2.2

production. It will require decades to phase coal out of the power supply mix.

- **Hypothesis 5:** Efficiency is a more successful strategy than increasing power supply, even renewable power supply

The methodology for answering these questions will be described in Chapter 2 (Methods). The various energy technologies and CCS options will be analyzed in detail and presented in the Chapter 3 (Results). The preferred options and actions will be presented in Chapter 4 (Discussion). Lastly, the key findings of this study will be presented in Chapter 5 (Conclusion).

2 Methods

This section outlines the methodology undertaken for the thesis. A brief overview of the process is first presented. Background information on the main tools, concepts and definitions used in the analysis are then provided, followed by an in-depth description of how they were applied to the stationary power sector.

2.1 Overview

Given the complexity of the stationary power sector, care was taken to properly understand the system through an extensive literature review of peer-reviewed journals and reports, attendance at two conferences[3] and a number of interviews with relevant experts in the fields of energy generation, CO_2 emissions and carbon capture and storage. A comprehensive list of the field experts consulted is provided in Appendix A. The stationary power sector was then analysed using a comprehensive approach for strategic planning in complex systems. The results from both the research and analysis form the supporting information from which we base our answers to the research questions.

2.2 Strategic Sustainable Development

This paper uses a framework for strategic sustainable development, widely known by business leaders as The Natural Step Framework. It is named after its founding organization, The Natural Step (TNS), an international NGO. The framework is a methodology for strategic sustainable development and consists of a Five Level Framework for planning in complex systems, a set of Sustainability Principles to set the minimum constraints for sustainability, the concept of backcasting for strategic planning, and an ABCD analysis tool to aid in the backcasting process. A description of each of these components is provided below.

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[3] Point Carbon's Carbon Markets Conference, Copenhagen, February 2006, and the World BioEnergy Conference in Jonkoping, May 2006

2.2.1 Five Level Framework

The Five Level Framework (Robèrt, et. al. 2005, xx) is a generic tool for comprehensive planning in complex systems. Each level of the planning process is distinct and hierarchical as well as interconnected such that feedback occurs between adjacent levels. The five levels and their connections are illustrated in Figure 2.1.

Figure 2.1. The Five Level Framework

1. Systems Level. At this level, the fundamental characteristics of the complex system are described. To avoid reductionism, all of the major components, interrelationships, and essential aspects of the system must be included.

2. Success Level. At this level, the objectives or desirable results that must be achieved within the systems are described.

3. Strategy Level. Strategic guidelines for achieving the goals defined at the Success Level are stated.

4. Action Level. Tangible events occur at this level in agreement with strategic principles identified at the Strategy Level.

5. Tools Level. There are three main types of tools at this level: systems, capacity and strategic. Systems tools make direct measurements on the Systems Level in order to learn more about the current status of the system. Capacity tools help communicate and clearly define the goals at the Success Level. Strategic tools are designed to ensure that events at the Action Level agree with strategic principles at the Strategy Level.

2.2.2 Backcasting

Backcasting is a concept that is essential for strategic planning in complex systems (Holmberg and Robèrt 2000). Unlike forecasting where future predictions are based on past trends, backcasting is a planning procedure in which first a successful outcome is imagined and then strategies that lead towards that outcome are determined. By looking backwards from that future and asking the question "what do we need to do today to achieve a successful outcome?" actions that can strategically progress towards the goal can systematically be undertaken.

2.2.3 Sustainability Principles

The word 'sustainability' is frequently used, but often without a clear indication of what that entails. In this thesis, sustainability is defined by adhering to four separate socio-ecological sustainability principles (SP´s) that were developed through a process of scientific consensus. These principles are:

In a sustainable society, nature is not subject to systematically increasing…

1. concentrations of substances extracted from the Earth's crust,
2. concentrations of substances produced by society,
3. degradation by physical means

and, in that society…

4. people are not subject to conditions that systematically undermine their capacity to meet their needs.

Collectively these principles are referred to as the sustainability principles, (also known in the business community as the TNS ‘system conditions’). and are considered to be the minimum requirement for which a sustainable society must comply (Holmberg et al. 1996 and Ny et al. 2006)[4].

2.2.4 ABCD Analysis

The ABCD Analysis (Robèrt 2000, 246-7) is a strategic tool belonging to the Tools Level of the Five Level Framework. It is called the ABCD Analysis after its four logical steps. It explicitly explains Levels 1, 2 and 3 of the Five Level Framework and provides a systematic approach to backcasting from objectives defined at the Success Level. Below is a description of each step of the analysis:

A Step. At this step, a shared understanding of both the Systems and Success Levels of the Five Level Framework is developed among the participants of the planning process. It is essential that these levels are defined as clearly as possible as they create the foundation from which all subsequent steps are based.

B Step. This is where backcasting is first applied. Here the participants scrutinize the current activities occurring at the Systems Level from the future perspective defined by the Success Level. In this manner, an understanding of how the system is not meeting the objectives stated at the Success Level is determined.

C Step. At this step, visions and solutions are brainstormed by the participants of the planning process. This is done again from a backcasting perspective in order to ensure that suggestions are aligned with Success Level objectives. The measures generated from this process correspond to the Strategies Level of the Five Level Framework. Conducting the C step often gives a clearer view of the current conditions in the B step, as carrying out the B step helps create the C step’s sustainable vision of the

[4] The initial phrasing of the principles was first published by Holmberg and Robèrt in 1996. Since that time the wording has been revised as reflected in Ny et al. 2006.

future. Thus, it is often helpful to conduct the B-C steps as an iterative process instead of a linear one.

D step. This is where prioritization of the brainstormed measures occurs. Each measure is examined individually in order to determine whether the answer is 'yes' to the following three questions:

1. Does this measure proceed in the right direction with respect to all of the sustainability principles?
2. Does this measure provide a flexible platform for further development?
3. Is this measure likely to produce a sufficient return on investment?

Based on these results, the best strategies can be determined and actions taken that will strategically lead the system towards the desired objectives.

2.3 Applied ABCD Analysis

The ABCD Analysis becomes a strategic tool for sustainable development when compliance with the sustainability principles is stated as a requirement at the Success Level of the Five Level Framework. This approach to planning in complex systems formed the backbone of our methodology, and was applied specifically to the stationary power sector. Additional tools such as a causal loop diagram (CLD) and a computer model were used at various stages during the analysis in order to develop a deeper understanding at the Systems Level as well as to help illustrate the effects of measures at the Strategies Level. An outline of how specifically the ABCD Analysis was applied to the stationary power sector is provided in the following sections. Although presented in a linear order here, feedback and iteration took place between steps, in a similar fashion as described for the Five Level Framework. The first three steps (A,B and C) are presented in the Results section. The prioritization questions of step D integrated well with our research questions, and for this reason step D was incorporated into the Discussion section.

2.3.1 A Step – Defining the System and Success

Defining the System. The scope of this thesis was determined to be the stationary power sector within society within the biosphere. From this starting point, the power generation technologies of a typical distributed power network and its interactions with society and the biosphere were analyzed. Additionally, emerging CCS technologies and their potential role in the stationary power sector were also considered.

A CLD was created in order to develop a shared mental model of the system. The function of a CLD is to map out the structure and causal relationships of a system in order to understand its feedback mechanisms. Feedback is responsible for changes within systems – action causing reaction. It is any action that causes an effect back to the starting point of the action, and is therefore both the cause and the effect. CLD´s are used to understand how a behaviour has been manifesting itself in a system so we can develop strategies to work with, or counteract that behaviour. A brief description on how to interpret CLD's is provided in the Results section.

To supplement our knowledge of how the system could be strategically changed over time, a bottom-up computer model of a stationary power network was developed. The model developed was not intended to be predictive with respect to reality, but rather to provide relative comparisons between scenarios and to illustrate the potential for specific actions to lead towards success, all within the context of the model and its assumptions. Comprehensive information on the computer model methodology, parameters and assumptions, and results are provided in Appendices B, C and D respectively.

Defining Success. In addition to compliance with the sustainability principles, goals specific to atmospheric CO_2 levels were also included.

2.3.2 B Step – Current Technology Score Card

The power generation and CCS technologies identified in the system were thoroughly researched in order to understand their characteristics. A rating system was developed that ranked each technology in terms of how well they currently complied with each sustainability principle. A sustainability ‘score card’ was then given to each technology and the results collated into a summary table.

Table 2.1. Sustainability rating system

++	An excellent performer in this category. No major issues.
+	Only minor SP violations, that can be addressed easily.
0	Tradeoffs exist. SP violations may be difficult to avoid or compensate for. Exercise caution in allowing this option.
-	SP violations exist that make this option a bad choice in all but temporary, transitional options, when accompanied by a phase-out plan.
--	Serious SP violations. Avoid at all costs.

2.3.3 C Step – Vision, Measures and Solutions

Envisioned Future. Characteristics of a sustainable stationary power sector were brainstormed. These ideas were then incorporated into a graphic representation of a future stationary power sector which was then referred to as the “desired future”.

Measures and Solutions. Through the application of backcasting, measures were listed that would strategically move the system towards the desired future. Measures that appeared to have similar results on the system were then clustered into groups and referred to as a strategy. Each strategy was then correlated to causal relationships in the system CLD and named in accordance with the actors that leveraged the system. Three strategies for strengthening the balancing loops were identified through this process. The first two strategies were essentially equivalent to the strategies of substitution and dematerialization identified in a review of the major methodologies for achieving sustainability (Robèrt et. al. 2002). We added a third strategy - abatement, defined as to nullify or diminish. Pollution abatement can be accomplished through any technology which chemically transforms harmful emissions into inert or more easily controlled substances. For example, pollution abatement technologies include exhaust scrubbers implemented in manufacturing facilities to neutralize acid-containing gases and convert them into solids, and catalytic converters on automobiles which reduce nitrogen oxides, which cause acid rain, into harmless nitrogen and oxygen.

2.3.4 D Step – Prioritization

In addition to the three prioritization questions used at the D Step, research relating to stationary power sector examples where measures were strategically implemented was also used to support our recommendations. The following two sections provide an overview to our approach at prioritization.

Prioritization Questions. Each measure was evaluated with respect to the three prioritization questions.

1. Does this measure proceed in the right direction with respect to success?

In addition to the sustainability principles, additional goals were included in our definition of success. For this reason, question 1 has been reworded to encompass all of the requirements outlined in our definition of success. The sustainability scorecards developed at the B step were used as the primary source of information for answering this question.

2. Does this measure provide a flexible platform for further development?

Each strategy was examined to determine if investments in these directions might lead down blind alleys. A flexible platform for further development would provide a technology basis for extending the state of the art with new advances, or would be compatible with alternate fuels, for instance.

3. Is this measure likely to produce a sufficient return on investment?

Each strategy was examined to determine what economical and environmental benefits they provided.

Prioritization Research. Specific research efforts focused on identifying existing prioritization methodologies which are currently employed in the stationary power sector was undertaken.

3 Results of ABCD Analysis

This section describes the results of the ABCD analysis of 'the stationary power sector within society within the biosphere,' including possible actions and their prioritization the project in the following sections:

- *A – The System*: A description of the stationary power sector within society within the biosphere, including major actors within the system and the interaction between them
- *B – Current Reality*: An analysis of SP violations today, as well as assets currently available for potentially addressing the problems.
- *C1 – Envisioned Future*: A potential future which is in compliance with the SP's is envisioned, and becomes the perspective from which backcasting is performed.
- *C2 - Strategies:* A brainstorm of the policies and power generation strategies and technologies to help us reach our envisioned future is described.
- *D step - Prioritization of Strategies*, is developed in Chapter 4, the Discussion section.

3.1 The System (A Step)

The A step in the ABCD process involves developing an understanding of the system. Here, we have broken it up into two parts:

- Defining the System - setting the boundaries of our study and describing how it works.
- Defining Success – what we would consider to be a successful outcome to backcast from.

3.1.1 Defining the System

This section provides an overview of the system we are studying: the stationary power sector within society within the biosphere. This corresponds to Level 1 of the 5-Level Framework.

We look at the various types of power generation in use today—fossil fuel, nuclear, and renewable—that are connected to a common grid from large point sources to produce electricity for commercial, residential, and industrial applications. Currently, power sources are predominately fossil fuel based. There is a significant amount of fossil fuel infrastructure in place, and the burning of fossil fuels produces CO_2 which is released into the atmosphere. Current trends indicate a continued reliance on fossil fuel power with continually growing energy demands. CCS is in the early demonstration phase and being considered for use with fossil fuel power plants to reduce CO_2 emissions.

A causal loop diagram was developed for the stationary power sector within society within the biosphere and is shown below in Figure 3.1. This diagram illustrates the main actors, major causal relationships and defines the boundary of the system being studied.

The grey circles represent variables (also known as actors) in the system. Each variable is labelled according to the action, event, or component that it is describing. The arrows show a causality, where a variable at the tail of the arrow causes a change to the variable at the head of the arrow. A plus sign near the head of the arrow indicates a change in the same direction while a minus sign indicates a change in the opposite direction. Loops are formed by connecting actors together with arrows pointing in the same direction (either clockwise or counter clockwise) that ultimately lead back to the actor where they started from. The letter "R" indicates that feedback in a loop is reinforcing behaviour in the *same* direction (also known as a reinforcing loop). The letter "B" indicates that feedback in a loop is balancing behaviour in the *opposite* direction (also known as a balancing loop). For simplicity, relative strengths and delays in causal relationships are not shown in the diagram and are instead discussed in the supporting text where appropriate.

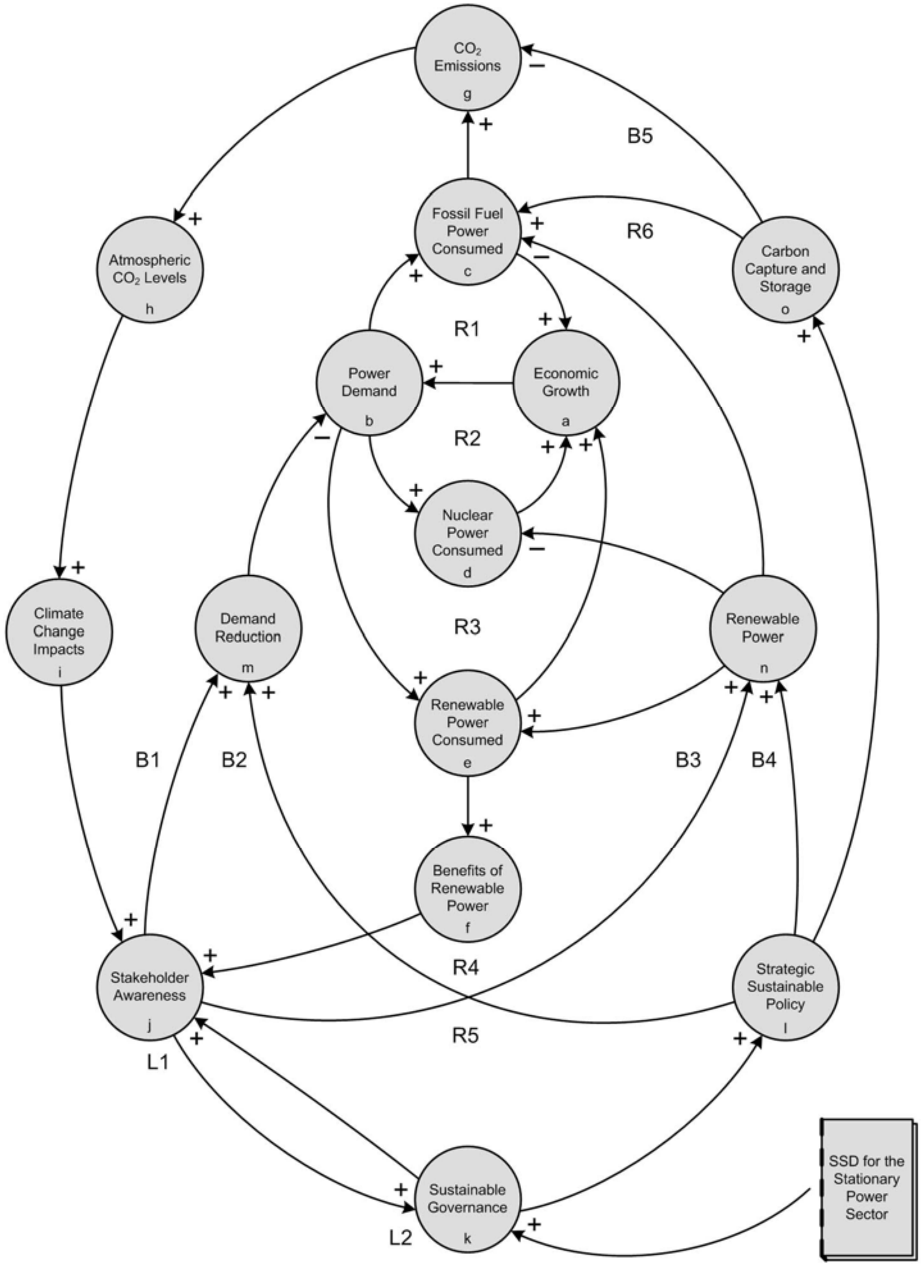

Figure 3.1. Causal loop diagram of the stationary power sector

Central to the diagram is the reinforcing loop between ‘Economic Growth,’ ‘Power Demand,’ and ‘Fossil Fuel Power Consumed’ (loop R1 – a,b,c,a). This has been the driving force of the global economic engine since the Industrial Revolution, and continues to be for the majority of the industrialized world. Two similar reinforcing loops exist in parallel to loop R1, R2 (a,b,d,a) and loop R3 (a,b,e,a). These loops operate in the same manner as loop R1, the only difference being the type of technology providing the power consumed. The relative strengths between loops R1, R2 and R3 are determined by the characteristics of the stationary power network being studied.

A major repercussion of loop R1 is the production of ‘CO_2 Emissions’ from ‘Fossil Fuel Power Consumed.’ These emissions have contributed to an increase in ‘Atmospheric CO_2 Levels,’ and as CO_2 is a primary greenhouse gas, it is directly responsible for an increase in ‘Climate Change Impacts.’ These impacts are now being recognized on a global scale which has created an increase in ‘Stakeholder Awareness’ (in this context, stakeholders refers to society at large). In a functioning democratic society, an increase in ‘Stakeholder Awareness’ should translate into an increase in ‘Sustainable Governance’ (a sustainability-focused governmental body intent on transitioning society towards sustainability). ‘Sustainable Governance’ in turn feeds back to ‘Stakeholder Awareness’ (through undistorted communication of relevant information for example) as well as being responsible for creating ‘Strategic Sustainable Policy.’ Through ‘Stakeholder Awareness’ and ‘Strategic Sustainable Policy,’ balancing loops have been put in place to address the ‘CO_2 Emissions’ associated with ‘Fossil Fuel Power Consumed.’ Three key actors in the system are integral to these balancing loops: ‘Demand Reduction,’ ‘Renewable Power’ and ‘Carbon Capture and Storage.’

Demand Reduction. The electrical power needs of the individual consumer are reduced, or in other words, the energy intensity of lifestyle is reduced. An increase in ‘Demand Reduction’ causes a decrease in ‘Power Demand.’ This weakens or slows loops R1, R2 and R3 and consequently reduces the ‘CO_2 Emissions’ associated with loop R1. The consumer (or Stakeholder) can have a great influence on ‘Demand Reduction.’ Actions such as turning lights off when not being used and installing solar hot water heating systems can greatly reduce electricity needs. This balancing loop is shown as B1 (b,c,g,h,i,j,m,b). ‘Strategic Sustainable Policy’ can also play an important role in increasing ‘Demand Reduction.’ Requirements for appliance power consumption and standards for building insulation are two examples of how this might be achieved. This balancing loop is shown as B2 (b,c,g,h,i,j,k,l,m,b).

Renewable Power. The development, deployment and utilization of renewable power generating technologies is considered here. An increase in the availability of ‘Renewable Power’ will increase the ‘Renewable Power Consumed’ (providing that renewable power supply utilization is prioritized over fossil fuel and nuclear). This will bias the mix of supply in favour of renewable power generation which strengthens loop R3 while weakening loops R1 and R2. In doing so, reducing the ‘CO_2 Emissions’ associated with loop R1. The consumer can have a direct influence on ‘Renewable Power.’ Net metering of installed solar panels or requesting renewable power from regional power supply companies are two ways of how this can be done. This balancing loop is shown as B3 (c,g,h,i,j,n,c). ‘Strategic Sustainable Policy’ can have a great influence on ‘Renewable Power.’ Grants for renewable power research and development, subsidies for increasing installed capacity, and taxes on fossil fuel are just a few of the ways that policy can do this. This balancing loop is shown as B4 (c,g,h,i,j,k,l,n,c).

As well as reducing fossil fuel power CO_2 emissions, there are a number of other benefits associated with increasing reliance on renewable power generation. This is represented by ‘Benefits of Renewable Power.’ These benefits include: reduced health impacts associated with the combustion of fossil fuel, enhanced power supply stability through source diversification, and improved energy security from reduced geopolitical tensions over fuel supply. This provides a feedback connection to ‘Stakeholder Awareness’ and creates two reinforcing loops [R4 (f,j,n,e,f) and R5 (f,j,k,l,n,e,f)], that further strengthen loop R3.

Carbon Capture and Storage. The development, deployment and utilization of CCS technologies in conjunction with power generation technologies is conducted. An increase in ‘Carbon Capture and Storage’ will result in a decrease of ‘CO_2 Emissions.’ ‘Strategic Sustainable Policy’ is the only actor in the system with the power to increase ‘Carbon Capture and Storage.’ This can be achieved by either implementing financial penalties on CO_2 emissions or by providing financial rewards for the sequestering of atmospheric CO_2. The Kyoto Protocol cap and trade system is one example of how this is currently being legislated. This balancing loop is shown as B5 (g,h,i,j,k,l,o,g). If CCS is applied to fossil fuel power generation technologies then a second causal connection is necessarily created. An increase in 'Carbon Capture and Storage' will increase 'Fossil Fuel Power Consumed' for two reasons. Efficiency losses from the capture and storage process, requires more fossil fuel to be consumed in order to produce the same amount of electrical power. Continued consumption of fossil fuels will also further promote development and deployment of fossil fuel power generation technologies – perpetuating our dependence on 'Fossil Fuel Power Consumed.' This creates a reinforcing loop R6 (o,c,g,h,i,j,k,l,o) that opposes the balancing effects created by 'Demand Reduction' and 'Renewable Power.'

Leverage Points. In the context of complex systems, the term 'leverage point' refers to a place of intervention where a small shift can produce big changes everywhere else (Meadows D, 1999). All of the balancing loops created by 'Demand Reduction', 'Renewable Power' and 'Carbon Capture and Storage' pass through 'Stakeholder Awareness.' This is an important actor in the system as it can directly affect all of the balancing loops identified for reducing CO_2 emissions. For this reason, we have identified 'Stakeholder Awareness' as a leverage point in the system, and have labelled it as L1. A sub-set of the balancing loops also passes through 'Sustainable Governance'. This actor also plays an important role in determining the effectiveness of these loops. Unlike 'Demand Reduction' and 'Renewable Power', where there is a causal relationship coming directly from 'Stakeholder Awareness', 'Carbon Capture and Storage' can only be influenced directly by 'Sustainable Governance'. Furthermore, 'Sustainable Governance' can increase 'Stakeholder Awareness' and indirectly affect the other balancing loops as well. For these reasons, we have identified Sustainable Governance as a leverage point in the system, and have labelled it L2. This thesis: *Strategic Sustainable Development (SSD) for the Stationary Power Sector* is intended to 'leverage' L2 by assisting policy-makers to make strategic decisions that will reduce and ultimately eliminate CO_2 emissions from the stationary power sector.

3.1.2 Defining Success

The second part of the B step in the ABCD process, Defining Success, corresponds to Level 2 of the 5 level Framework for Strategic Sustainable Development. As a bare minimum for sustainability, this success must include compliance with the 4 Sustainability Principles.

As discussed in the introduction, anthropogenic CO_2 emissions have increased atmospheric CO_2 levels to well above that of previously recorded natural variations. In addition to reducing CO_2 emissions to within the carrying capacity of the bio-sphere, it is the shared view of the authors that atmospheric CO_2 levels must be restored back to within natural variations. Thus, for the purposes of this study, we have defined 'Success' to mean both compliance with the sustainability principles and that atmospheric CO_2 levels have stabilized below 500 ppm, and are trending down towards 280 ppm. The threshold of 500 ppm CO_2 was selected as this is a level which is generally believed to be accessible with currently identified technologies within a time frame of fifty years (albeit with monumental effort and investment) (Pacala and Socolow 2004, 968). The ultimate target of 280 ppm represents the upper limit of the natural variation of CO_2 concentration, which was originally reported in the Vostok ice core study, and has been confirmed by the EPICA ice core study (Petit et al. 1999). In order to reach these targets and restore atmospheric CO_2 concentrations within a reasonable time frame, we hypothesize that CCS technologies may be required.

3.2 Current Reality – Power Generation (B Step)

The B step includes an analysis of current reality from the perspective of sustainability principle violations within the stationary power sector and the assets currently at our disposal to address the problems. This section surveys the stationary power generation landscape to assess the sustainability aspects of the current supply mix and evaluate our future options.

The following are some of the major Sustainability Principle (SP) violations that were identified by examining the stationary power sector described in the A-step. They will be explored in more detail in the individual sections.

SP I	• CO_2 emissions from fossil fuel power plants • Mercury, lead, and sulphur emissions from fossil fuel power plants • Uranium and other isotopes from uranium mining for nuclear power plants
SP II	• SOx, NOx, and particulate emissions from fossil fuel burning • Aerosols • Radioactive waste from nuclear power facilities
SP III	• Habitat and biodiversity loss from fossil fuel extraction • River interference and flooding from hydroelectric dams • Infrastructure (pipelines, power lines) • Fossil fuel extraction waste products (tailings, ponds) • Depleted aquifers from fossil fuel extraction (e.g. tar sands) and nuclear power plants
SP IV	• Resource exploitation of underdeveloped fossil fuel-rich countries, which supports oppressive regimes • Re-location of people and villages because of valley flooding from hydro-electric • Further use of fossil fuels as well as nuclear power leads to decrease of national security due to possible targets for terrorist attacks, reduced self-reliance at regional level and geopolitical tensions linked to such problems. • Linkage between nuclear power and nuclear arms. • Competition for diminishing fossil- and nuclear- fuel leads to increased risks for war

Each technology or group of technologies is evaluated for compliance with the Sustainability Principles and given a scorecard according to the rating system presented in the Methods section (Section 2.3.2).

Fossil Fuels. The major fossil fuels explored in the B step are coal and natural gas technologies. Oil is not used to a great extent in electricity generation. Coal is the most abundant fossil resource and is used to produce 40% of the world's electrical power (IEA 2005a). Around 90% of coal-fired power plants utilize pulverized coal combustion (PCC) technology, with one of three variations: sub-critical, supercritical and ultra-supercritical (depending on the pressure level of the steam system). There are several emerging power generation strategies with an emphasis on "clean" coal, or near-zero emissions technologies (ZETs), which prominently feature integrated combined cycle gasification (IGCC) due to its high efficiency and amenability to CCS and mitigation of other pollutants, though it is currently a small part of the mix (<10%). Natural gas combined cycle (NGCC) is also evaluated, as the main competitor to coal powered electricity generation.

Renewable Energy Technologies. When sustainable electricity alternatives are proposed they are usually referred to as 'renewable energy;' however, as with 'sustainability' there are a variety of definitions of 'renewable.' A brief survey of definitions reveals common characteristics:

1. Natural replenishment, within a reasonable time frame (at most one generation to one lifetime). (BCH 2002a)

2. Exploitation of the resource occurs at a rate that does not lead to depletion (i.e. systematic degradation of the resource) (CRS 2001a)

3. The focus is on the characteristics of the energy source, rather than the technology employed (NAAG, 14-15)

We assess the sustainability aspects of renewable energy technologies involved in the stationary power generation sector. That includes options such as wind, solar, hydroelectric, and biomass. Options such as ethanol are not considered, as they are not widely used for electricity generation due to the much higher efficiencies from burning biomass directly without first converting it to a liquid fuel. It should be noted that 'renewable energy' does not implicitly mean that the technology is sustainable, it just means that the fuel supply is renewable. We will define Renewable Energy as energy forms derived directly or indirectly from solar radiation, from tides and from the heat of the Earth's core. (B.C. Hydro 2002).

3.2.1 Pulverized Coal Combustion

Finely powdered coal is burned in air within a large combustion boiler, and the heat produced is used to raise steam which drives a steam turbine. A range of efficiencies can be obtained for this process, depending mainly upon the steam pressure. At pressures above the supercritical point of water (22.1 MPa), greater thermal efficiencies can be achieved, on the order of 42 – 47% for the most advanced new technologies. Supercritical unit sizes up to 1000 MW are routinely operated worldwide. Efficiencies up to 50% can be achieved with even higher pressures (35 MPa) with the 'ultrasupercritical' process currently under development The post-combustion effluent is known as 'flue gas,' and is composed of N_2 (70%), CO_2 (15-25%), and H_2O, and also contains SO_x, NO_x, particulates and heavy metals such as mercury which are removed by various scrubbing technologies before the flue gas is released to the atmosphere. Due to the use of air for combustion, the CO_2 in the flue gas is diluted by a large volume of nitrogen, which has implications for appropriate sizing and cost of the CO_2 separation system, when CCS is considered. One possibility for enabling the compatibility of PCC with CCS is 'oxy-fuel' combustion, where oxygen is used in place of air in the combustion boiler and produces an effluent which is more highly concentrated in CO_2.

Table 3.1. Sustainability assessment for PCC power generation

Right Direction		
SP I	--	Emissions of CO_2, heavy metals and particulates.
SP II	-	Emissions of SO_x and NO_x (abatement required by law in OECD, but not in developing countries.
SP III	-	Land disturbance (especially with "mountain-top removal"). Surface and groundwater contamination. Methane emissions.
SP IV	-	Adverse health impacts due to particulates, mercury and acid gases where they are not mitigated. Safety hazards for miners.

3.2.2 Integrated Combined Cycle Gasification

IGCC technology can convert a wide range of carbon-containing feedstocks (high and low quality coal, oil, biomass, or waste) into a 'synthesis gas' which is a mixture of carbon monoxide and hydrogen. This synthesis gas (or 'syngas') can be used in a number of ways – as a fuel to generate electricity or steam, or as a chemical feedstock for the production of a range of industrially important chemicals. These chemical products include ammonia, methanol and hydrocarbons ranging in length from methane (CH_4) up to diesel (chains longer than $C_{16}H_{34}$) via the Fischer-Tropsch chemical process.

Combined-cycle technology utilizes two turbines: a combustion turbine, where the syngas is burned in air, and a second steam turbine which utilizes steam raised by the waste heat of the combustion turbine. Because waste heat is utilized, combined cycle efficiencies are around 60%, compared to ~35% for a combustion turbine alone.

Because oxygen is used rather than air in the gasification process, the effluent gases are highly concentrated in CO_2, making IGCC very amenable to CCS. Pollutants such as sulphur, and mercury are converted to their elemental or reduced forms and are readily captured as sulphur, ammonia and metallic mercury. Particulates are also removed before further processing. IGCC is clearly a favoured zero-emissions technology, and is currently receiving significant levels of government funding for research, development and deployment in the US and in Europe (Henderson 2003, 34).

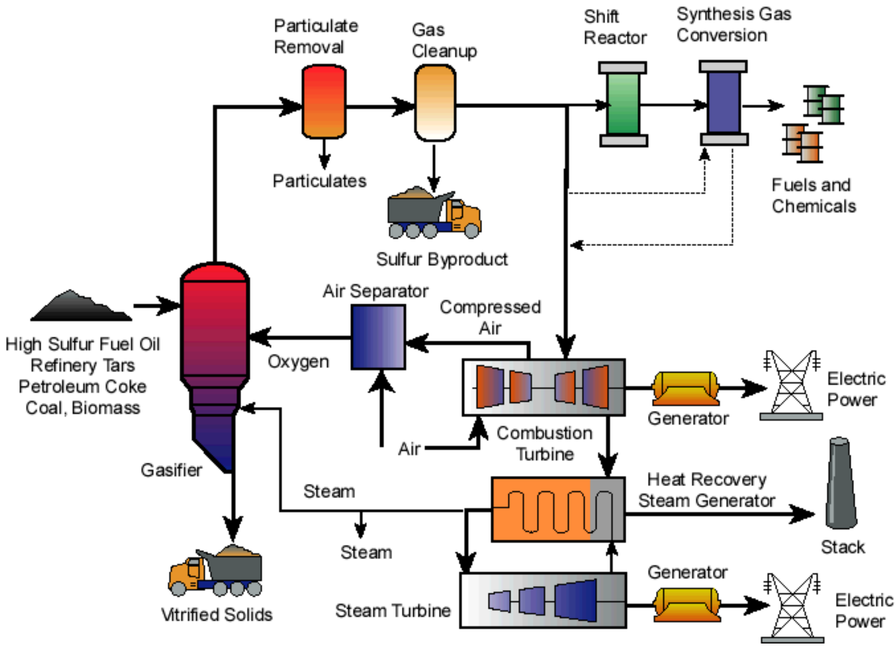

Figure 3.2. The IGCC process (GTC, 2005)

There are 385 IGCC units in operation worldwide. Of these, only four of are used for power generation while the others produce chemicals. Key barriers to more widespread adoption include higher cost and lower reliability than PCC technology.

Table 3.2. Sustainability assessment for IGCC power generation

Right Direction		
SP I	+	Emissions of CO_2, (Heavy metals and particulates greatly diminished relative to PCC)
SP II	+	Emissions of SOx and NOx are mitigated by scrubbing technology
SP III	-	Land disturbance (esp. with "mountain-top removal"). Surface and groundwater contamination. Methane emissions
SP IV	+	Safety hazards for miners

3.2.3 Natural Gas

Most power plants built in the US in the 1990's utilized NGCC technology, in a drive to meet tougher air standards by moving away from dirty, polluting coal. The advantages of natural gas (also methane or CH_4) over coal are that particulate matter is not produced in the combustion, SO_x and NO_x are minimal, and there are no heavy metals. Natural gas combustion is more exothermic than coal, resulting in higher temperatures, and thus higher efficiency in energy conversion. When burned, natural gas produces less CO_2 per unit energy than coal. However, despite these advantages, limited supply of natural gas (particularly in North America) has caused the cost of the fuel to nearly triple over the past three years, making this an economically unfavourable option. In the 1990's, natural gas wellhead prices were in the range of \$1.50 - \$2.00/MMBtu, but today they are highly volatile, and have ranged from \$6.00 to \$14.00/MMBtu in the past twelve months. Gas production from the Gulf Coast region is particularly vulnerable to disruption during the hurricane season, as Hurricane Katrina demonstrated in 2005. This supply constraint is the motivation behind developing liquefied natural gas (LNG) infrastructure, which is imported from areas where it is plentiful, such as the Middle East or Russia. Higher natural gas prices are a key driver for reverting to coal-fired power generation for new installations. Currently, natural gas fuels 19% of the world's electricity production.

Table 3.3. Sustainability assessment for NGCC power generation

Right Direction		
SP I	**-**	Emission of CO_2 to the atmosphere (however, it is less than that of coal)
SP II	**0**	Emissions are inherently cleaner than when coal is burned
SP III	**-**	Disturbance of the environment due to natural gas extraction, and LNG terminals are potentially damaging to sensitive coastal areas
SP IV	**0**	Risk of LNG terminal catastrophic explosion

3.2.4 Nuclear

All commercial nuclear reactors operate on the principles of nuclear fission. During this process, the atoms of certain isotopes of uranium and plutonium are split and energy is released. 438 commercial nuclear reactors were operating at the end of 2000 with a net generating capacity of about 360 GW. The annual amount of uranium required to fuel this capacity is estimated to be 64,014 tonnes (Nuclear Energy Agency 2001, 10).

Reactors can be divided into two main categories; thermal slow reactors and fast neutron reactors. Thermal slow reactors use enriched or natural uranium for fuel, while fast neutron reactors require highly enriched fuel (sometimes weapons grade) or plutonium to sustain the fission process. In both cases, the energy released is in the form of heat, which is typically converted to electricity by means of a steam turbine. Considerable infrastructure is required to support a controlled nuclear reaction, particularly with respect to safety and cooling systems. For this reason, nuclear power generating facilities are best suited for medium and large-scale power generation in which electricity is supplied on a continuous basis.

Uranium is a radioactive metal that occurs throughout the earth's crust. In certain locations, concentrations are sufficiently high enough that extraction of it for use as nuclear fuel is economically feasible. At end of 2000 there was approximately 3,933,000 tonnes of uranium (≤USD130/kgU) in known reserves, which based on the current level of consumption, is expected to last just over 50 years. The total undiscovered conventional resources, however, are estimated to be approximately three times this amount (Nuclear Energy Agency 2001, 9). Advanced fast reactors use plutonium (created from uranium during the reaction) as part of the fuel source, allowing 60 times more energy to be generated from the original uranium. These reactors are expensive to build when compared to thermal slow reactors, and currently there is only one in operation. As significantly less fuel is required for there operation they may become cost competitive if and when natural uranium resources run scarce (World Nuclear Association 2005).

There are many steps involved in the nuclear fuel cycle. These include; mining, processing, enriching, storage, reprocessing and disposal.

Throughout this process the fuel becomes more and more radioactive, and consequently safety measures become more stringent. High-level waste accounts for 95% of the radioactivity produced, and a typical large 1000 MW_e reactor will produce 25-30 tonnes of this material per year (World Nuclear Association 2001). This material will remain highly radioactive for thousands of years, and even after 50 years of commercial operation of nuclear power, no country has successfully developed a means for disposing of nuclear waste safely over the time period during which it will remain hazardous. This is a serious concern from both an environmental and economic perspective as the long term effects of systematically accumulating high-level nuclear waste in the bio-sphere are yet to be realized.

Table 3.4. Sustainability assessment for nuclear power generation

Right Direction		
SP I	**0**	CO_2 emissions from uranium ore mining and processing heavy metals and low concentration radioactive materials in tailings.
SP II	--	High-level nuclear waste (plutonium and other fission products) created during normal operation. Reactor core failure and nuclear waste has the potential to release radioactivity to the air and ground water.
SP III	-	**Large scale mining operations to obtain fissionable materials can degrade natural systems.**
SP IV	--	Fear of nuclear weapon proliferation. Severe health effects in the event of release of radioactivity.

3.2.5 Photovoltaic Solar

Photovoltaic (PV) cells convert sunlight directly into electricity. Technology advancements in this industry are rapid, with new materials being introduced all the time. The sustainability aspects of each new material need to be weighed individually. There are two major categories of PV cells: crystalline silicon and thin-film.

Silicon crystal cells are the most common. Thin wafers of silicon are created in the same process used to create microchips, requiring much energy to produce—hence, the high cost. Within this technology, monocrystalline cells have the highest efficiencies, but require the most energy to produce. Polycrystalline and ribbon cells are easier to produce, but are less efficient. Silicon solar cells are often mounted in aluminum frames, which also require a significant energy investment to manufacture.

A common misconception is that PV cells require more energy to manufacture than they will produce in their lifetime. This is not true. While energy payback times will vary depending on latitude and available sunlight in a given location, the energy payback time of present-day systems may be 2-3 years in a sunny climate and 4-6 years under less favourable conditions. Currently-produced PV cells have a lifespan of at least 25-30 years. (Alsema and Nieuwlaar 2000, 1003)

Thin film technologies are the third generation of PV, and require significantly less materials and energy to produce than silicon crystal cells. The films can be applied to a variety of materials, including flexible plastic, and even used as window glazing. There are a number of thin film technologies, produced from a variety of materials. Some of those materials are rare, leading to potential SP II problems. The most common materials at this time are copper indium gallium selenide (CIGS), chalcogenide (CIS), and cadmium telluride (CdTe). Gallium arsenide (GaAs) multijunction cells are another very efficient (up to 40%), but very expensive (US$40 per cm^2) technology. They have an advantage of working well at higher temperatures and can be combined with solar concentration using mirrors or Fresnel lenses. Other emerging technologies exist as well. Germanium is being researched to generate electricity directly from the infrared spectrum. Organic semiconductors and light-absorbing dyes are being developed for thin film PV. (Chopra, Paulson and Dutta 2004)

The fuel for solar energy is sunlight, which is free. Availability varies by latitude as well as cloud and vegetation cover. One major advantage PV has over other renewable energy sources is that peak power usually corresponds with peak demand – in the middle of the day, when businesses are running, and air conditioning is in maximum use in warmer climates.

Grid-connected solar PV has increased from 0.16GW in 2000 to 1.8 GW in 2004, a 60% growth rate (REN21 2005, 6). Along with the rapid increase of PV deployment, costs have been dropping accordingly over the past few decades. Costs will likely continue to drop in the future as the technology matures and efficiency improves.

Solar photovoltaics can be an effective method for reducing CO_2 emissions. Accounting for all the production costs, the CO_2 emissions due to a PV power plant over its entire lifespan is similar to the first 4 years of operation of a coal plant (Tahara et al., S619).

Table 3.5. Sustainability assessment for PV power generation

Right Direction		
SP I	+ -	**Silicon crystal solar technologies** are relatively benign. **Thin film technologies** may include elements such as gallium, arsenic, and cadmium.
SP II	++	No major violations not already covered by SP I.
SP III	+	Mining operations. Solar power facilities could take up large areas of land if not installed on existing rooftops or barren areas.
SP IV	+	Mining conditions and developing world manufacturing plants may involve human rights violations.

Silicon crystal photovoltaics are in compliance with all the Sustainability Principles. Current thin film PV technologies contain rare, toxic mined elements which violate the SP's. There are several different types of thin film materials still in the early research phases, however, which may be suitable from a sustainability perspective.

3.2.6 Wind

Wind is an indirect form of solar energy created by regional air pressure differences caused by unequal solar heating effects, most often between land masses and oceans. 'Wind power' refers to the technology of converting the kinetic energy in the wind into electrical energy.

Wind is available all over the Earth, however strong, consistent winds are not common and often not close to power grid connections. The 'practicable' global wind resource is very difficult to estimate given the lack of comprehensive wind data for all areas but the European Wind Energy Association estimate that it would be practicable for wind to supply more than 20% of the world's electricity by 2040. (EWEA/Greenpeace Wind Force Report 2005)

As with PV technologies, there is sometimes a misconception that wind turbines require more energy to manufacture and install than are generated over the turbine's lifespan. Numerous studies have shown this to be a fallacy. For example, one recent study calculated an 'energy payback ratio' (calculated by dividing the total amount of energy produced by a plant by the total energy consumed by the plant) of 23 for wind. (White et. al. 1999).

Wind supplies over 500 billion kWh of electricity which is just 0.3% of global electricity production. However in some power grids, for example in Northern Germany, wind provides in excess of 20% of the power used and installed generating capacity has been growing by an average cumulative rate of 28% 2001 to 2005 (EWEA/Greenpeace Wind Force Report 2005)

Table 3.6. Sustainability assessment for wind power generation

Right Direction		
SP I	++	Turbine generators require the use of common metals like iron, copper and aluminium. Once installed wind turbines do not violate SP1.
SP II	+	Once installed wind turbines do not violate SP2.
SP III	++	Physical impacts are small and there is good opportunity for multiple uses of lands where turbines are installed. Small numbers of turbine-related bird deaths did occur in the past with smaller, inappropriately-sited turbines. With modern turbines the observed bird mortality is extremely low. (AWEA 2006, 1)
SP IV	++	Visual impact can be perceived negatively or positively. Noise was an issue with earlier machines but is no longer a problem with today's larger, slower-moving blades. (Boyle 2004, 270)

3.2.7 Hydroelectric

Hydroelectric power uses water and gravity to create electricity. It can be divided into a few different categories, depending on the size of the installation. Definitions vary, but the following categories are common:

- *Large Scale* – Generally, hydro power plants over 10 MW in size. Large dams are constructed to create an artificial lake behind the dam. Water is directed through turbines in the dam to the river below.

- *Small Scale* – Hydro power plants under 10 MW in size, still usually involving dams. Sometimes, turbines can be retrofitted to existing dams to generate power.

- *Micro Scale* – Hydro plants 100kW or smaller in size, usually run of the river, which does not require construction of dams.

Hydroelectric power was once hailed as the cleanest and most environmentally-friendly of all energy sources. Although operational emissions of CO_2 are negligible, hydroelectric power is not free from environmental effects.

Traditional large-scale hydroelectric plants involve the construction of large dams, which require massive quantities of concrete to construct, and cause flooding above the dam. This flooding displaces wildlife and sometimes human populations, and causes methane (another greenhouse gas) to be released as former dry-land vegetation decomposes underwater. In some cases, the damming can also interfere with salmon migration. Even when fish ladders are constructed to allow most of the fish to navigate back upstream to spawn, many smolts cannot survive the trip downstream through the turbines—8 to 10% are killed in the turbines at each dam (Montaigne 2001, 25). As with other forms of renewable energy, the fuel is free. Availability of hydropower is limited to the amount of flowing water in a region.

Construction of a 10MW hydroelectric dam will contribute the same amount of CO_2 emissions as running a 10MW coal plant for 0.41 years. (Tahara, *et al.*, S619)

Table 3.7. Sustainability assessment for hydroelectric power generation

Right Direction		
SP I	++ 0	**Micro:** No significant problems specific to micro hydro. **Small & large:** A large amount of cement is used in the construction, releasing CO_2. Upstream vegetation flooding releases CH_4 and reduces terrestrial sink capacity.
SP II	++	No significant problems related to hydro power.
SP III	++ -	**Micro:** Minimal impact on natural systems. **Small & Large:** Upstream habitat flooding, disruptive to fish populations, affects erosion and sedimentation patterns.
SP IV	++ -	**Micro & small:** Minimal impact on human needs. **Large:** Upstream flooding has sometimes displaced people living in the area

3.2.8 Ocean – Tides, Waves, Currents

Ocean power refers to power derived from tides, waves and currents. Waves are created by wind passing over open water, and therefore can be considered a form of solar energy. Tides result from the gravitational pull of the moon as it orbits the Earth. Currents can result from wind, tides, solar heating or Earth rotational effects.

Tides, currents and waves represent huge movements of water and thus huge energy flows. Attempts to tap into these flows for the purposes of power generation have begun only recently. These technologies have significant potential but as of yet contribute only a very small percentage to the global power supply (tidal) or are still only experimental (currents and waves). Nonetheless, we have chosen to include them because they hold promise of being a useful part of a diversified renewable energy generation system. Compared with wind and solar power ocean power has two important advantages: high power density and a high number of full load hours / year. (Leijon 2006)

Tidal Power –Barrage-type tidal power involves building barriers across a tide-flooded estuary and channelling flood (upstream) and ebb (downstream) tide waters through turbines to generate power. Since appropriate estuaries and tidal ranges are very site-specific tidal power is a limited generation option. In countries with suitable sites however, tidal power can make a significant contribution; in the U.K. tidal power has an estimated commercial potential of 14%. (Boyle 2004, 223)

Tidal stream technology involves the installation of turbines where there is a strong current or tidal stream, without building a barrier and thus avoiding potential large-scale environmental interference.

Wave Power – A variety of strategies are currently under development with several operational demonstration installations currently generating power but no plans yet for large-scale commercial projects.

The technical available resource of wave power is difficult to assess given the early level of exploration and development. Assessments of countries with long coastlines and frequent stormy conditions, like Chile and the U.K., have identified practicable annual production of 40TWh (Leijon, 2006) and 50TWh (U.K. Department of Trade and Industry, 166). These quantities represent potential for significant ocean power contributions.

Current Power – This technology is in a similar state of development as wave power.

As of the end of 2004 global installed capacity of ocean power was 0.3GW, or less than one tenth of one percent. Table 3.8 assesses ocean power technologies for their sustainability aspects:

Table 3.8. Sustainability assessment for ocean power generation

Right Direction		
SP I	+	Turbine generators require the use of common metals like iron, copper and aluminium. Once installed wind turbines do not violate SP1.
SP II	+	Once installed wind turbines do not violate SP2.
SP III	++	The installation of seabed-mounted or floating generating machinery and cabling can have a small to neutral effect on the local seabed. - Rotating turbine blades can physically damage marine fauna, if poorly designed and located. - Large-scale diversion structures can affect estuary ecosystems by altering salinity, turbidity and chemistry of the sea-water which changes the species mix, while not necessarily leading to a net reduction in biodiversity. (Boyle 2004, 211)
SP IV	++	Large scale alterations to tidal and current flows and large arrays of offshore wave generators could effect habitats that people rely upon for food, employment, and transportation.

3.2.9 Biomass

Biomass refers to a variety of plant-based materials which can either be combusted for power generation, or alternatively, converted into liquid fuels such as ethanol, methanol, and biodiesel. The latter are typically produced from food crops, such as corn, sugar cane and oilseeds. These are primarily viewed as substitutes for petroleum-derived gasoline and diesel in the transportation sector, and are not generally considered as fuels for power generation. It is more efficient to burn biomass directly than to convert it to liquid fuel before burning in a power plant. Biomass can be utilized through combustion or gasification, analogous to coal. The source of biomass for power generation can be different waste streams, such as agricultural wastes (stalks, leaves, straw, sugarcane bagasse) or wood waste (woodchips, sawdust, pulp). Rapidly-growing “energy crops” are also being evaluated as a fuel source, including trees (e.g. poplar, maple, sycamore), grasses (e.g. switchgrass) and algae. Up to 5-15% biomass fuel can be readily co-fired with coal without changing operating conditions, while yielding significant reductions in NOx, SOx and CO_2 (Singh and Fehrs 2001).

Assuming that the biomass is replanted, the combustion of biomass fuel for power generation is considered to be 'carbon neutral,' since CO_2 is taken up from the atmosphere through photosynthesis in order for the plants to grow. Of course, any fossil fuel inputs required for harvesting, transportation and processing must also be considered, as well as changes in land use.

The global potential for biomass energy production in 2020 will be ~7,000 Mtoe, including crop residues, wood, energy crops, animal waste and municipal waste (Fischer and Schrattenholzer 2001). Biomass is widely available and widely utilized, and there is potential to produce bio-energy crops on marginal land, thus minimizing competition for prime agricultural land. It is a proven commercial power generation option - in the US, 61,265 megawatts (MW) were produced from biomass combustion in 2003 (EIA 2006b, 24).

Table 3.9. Sustainability assessment for biomass power generation

Right Direction		
SP I	+	Biomass combustion is theoretically carbon neutral, however, some fossil inputs are required for harvesting and transport.
SP II	++	No NOx, SOx or particulates. No violations.
SP III	+	Land management is a concern, especially if land is cleared specifically for bio-energy crops, or if forests are not harvested in a sustainable manner (e.g. harvesting the "interest" while leaving the "capital" in place). Potential violation.
SP IV	**0**	Land use competition with food crops is a concern, if prime agricultural lands are required for bio-energy crops.

3.2.10 Geothermal

Geothermal energy is defined as heat from the earth. This thermal energy continuously flows from the mantle to the surface of the earth and is expected to do so for billions of years. As this heat source is essentially limitless, geothermal energy is considered to be renewable. The flow of thermal energy is more intense at tectonic plate boundaries, the most obvious manifestations of which are active volcanoes and high temperature geothermal fields. The world potential of known geothermal resources suitable for electricity generation is estimated to be 240 GW. Theoretical estimates suggest that the potential of hidden resources could be 5-10 times larger than this amount (Stefansson 2005, 1). Currently 24 countries generate power from geothermal resources, the total combined installed capacity of which is 8.9 GW (Bertani 2005, 1)

Below the earths crust, magma (molten rock) heats water contained in rock pores and fractures, creating pockets of hot water and steam known as geothermal reservoirs. Wells are drilled into these reservoirs and the water and or steam is extracted to the surface and used to generate electricity. Geothermal reservoirs vary greatly in terms of size, depth, pressure, temperature and composition and therefore require different electrical generation technologies to optimize the energy conversion.

There are three basic types of geothermal electrical generation systems: binary, dry steam (or 'steam'), and flash steam (or 'flash'). All three use a turbine for electricity generation but differ in operation with respect to the working fluid(s). Recent improvements in the binary system have made it economically possible to generate electricity from lower reservoir temperatures of 100 to 150 °C. This has significantly expanded the global potential for geothermal electricity generation as lower grade thermal reservoirs can now be competitively utilized. As geothermal energy is continuous, power plants can be designed to operate with capacity factors up to 95% (Kagel 2005, 4-8).

Geothermal reservoirs can contain non-condensable gases such as CO_2 and hydrogen sulphide. Depending on the electrical generation system, these gases can pass through the turbine and vent to the atmosphere. A power weighted average for 85 geothermal facilities calculated the CO_2 emissions to be 0.122 kg/kWh. In most cases, the process of natural CO_2 generation is independent of geothermal exploitation (Bertani 2002).

Geothermal heat pumps use geothermal energy for heating or cooling purposes, but do not themselves generate electricity. As such, they are not addressed directly in this report, but are considered an important way of reducing electrical consumption for heating in buildings.

Table 3.10. Sustainability assessment for geothermal power generation

Right Direction		
SP I	+	Geothermal exploitation can release carbon dioxide and hydrogen sulphide to the atmosphere that otherwise would have remained in the lithosphere
SP II	++	None
SP III	++	None
SP IV	++	Visual impact produced by large quantities of steam could be perceived negatively

3.3 Current reality – Carbon Capture (B Step)

Among our assets in dealing with current violations of sustainability problems, is CCS. These technologies are still in the experimental stages and are being tested in combination with fossil fuel burning and extraction. CCS has the potential to reduce the CO_2 emissions from fossil fuel consumption in the short term, and help remove previous anthropogenic emissions when combined with biomass in the long term.

Carbon capture from power plant exhaust is the first phase in CCS where the CO_2 is separated from the exhaust gases to be stored. This section explains the three main carbon dioxide separation technologies considered for commercial applications: sorbents (solvents), membrane, and cryogenic distillation. Mineral carbonation, which combines the capture and storage phases, is discussed later along with carbon storage options. Sorbents/solvents and membrane separation can be applied to either pre- or post-combustion technologies, while cryogenic separation is specific to oxyfuel combustion. The preferred option for commercial applications is currently sorbent separation with post combustion gas streams.

3.3.1 Separation with Sorbents

In this process, the CO_2-containing gas stream is passed through an ‘absorber’, a vessel containing an aqueous alkaline solvent (usually an amine) that is capable of selectively capturing the CO_2. The gas stream exits the vessel and is released to the atmosphere while the CO_2 ‘rich’ solvent is circulated to a second vessel known as a ‘stripper’. Heat and/or pressure is used in the stripper to liberate the CO_2 which can then be further compressed and transported. The ‘lean’ solvent is then pumped back to the absorber to complete the cycle. The size of this system must be matched to the flue gas stream being purified, which for power plant faculties, is quite large. This translates into significant additional equipment and energy requirements which tend to lead to an important efficiency penalty and added cost. The amount of CO_2 removed from the flue gas stream is typically between 80% and 95% (Metz et. al. 2005, 115). The exact value of which is determined by the trade-off between additional operating costs and the amount of CO_2 removed.

3.3.2 Separation with Membranes

Membranes are specially engineered materials that allow for selective permeation of a fluid through them. Fluid pressure, specifically the partial pressure of the fluid to be separated, is the motive force behind the separation process. In flue gases, the CO_2 partial pressure is low which results in a low percentage of CO_2 removed. To increase the effectiveness of separation, the flue gas pressure can be boosted, but this will result in higher energy penalties than that of sorbent separation. Membrane separation is currently used in many high pressure industrial applications; however, they have yet to be demonstrated in the large-scale demanding conditions of stationary power generation.

3.3.3 Separation by Cryogenic Distillation

Instead of separating CO_2 from the flue gas stream, O_2 is separated from the air before combustion occurs. This produces a CO_2 rich stream which requires little purification before compression and transport. This process is referred to as oxyfuel combustion, and the overall CO_2 capture efficiency is typically close to 100% (Metz et. al. 2005, 122). Cryogenic distillation is the most economical method of producing the large quantities of O_2 required for large scale power plant operations. In this process O_2 is removed as a liquid from the other constituents of air in a process by which the air is compressed, cooled and separated in a distillation column. Significant amounts of electrical energy are required for this process as the pressures needed for separation are high and the volume fraction of O_2 in air is quite low.

3.3.4 Capture Systems Emissions

Analysis of both current and emerging capture technologies suggest that they can reduce the power sector's CO_2 emissions by 90% or more (Metz et. al. 2005, 143). However, in addition to producing concentrated CO_2 for storage, capture systems in most cases will also produce solid and/or liquid wastes as well as emitting a flue gas to the atmosphere. The solid and liquid wastes vary depending on the feed stock and separation processes, and will generally be incinerated, in some cases this waste may be classified as hazardous. Concentrations of harmful substances in the depleted flue gas, primarily SOx and NOx will be similar or lower to that of a flue gas from a power plant without carbon capture. If additional trace substances such as HCl and Hg are captured along with the CO_2 then their emissions to the atmosphere will be reduced but health and safety as well as environmental impacts may occur at the storage site. As solid and liquid wastes are specific to the separation technology and feed stock used, and recognizing that large scale CO_2 applications are still being developed, further details on environmental implications were not investigated.

Retrofit. CO_2 capture can be retrofitted to existing power plants providing that adequate site space is available and that there is sufficient plant life remaining to justify the large capital expenditure. Older power plants that operate at low energy efficiencies will suffer proportionality more from the auxiliary requirements of carbon capture than those more recently built. This could lead to early retirement of some power plants if CO_2 capture was introduced rapidly into the power sector.

Table 3.11. Sustainability assessment of CO_2 capture technologies

Option	**SP Compliance**			
	I	**II**	**III**	**IV**
Sorbents	-	-	+	+
Membranes	+	+	+	+
Cryogenic	+	+	+	+

This table summarizes the Sustainability Principle compliance of the carbon separation technologies. Sorbents are not recommended due to the potential for leakage of substances, both man-made, and mined materials into the environment. Separation with membranes and cryogenic distillation are in compliance with the principles, although the former is preferred due to the large amount of energy required for cryogenic distillation.

3.4 Current Reality - Carbon Storage (B step)

The following CO_2 storage options are explored in this section:

- Geological Storage
    - Saline
    - Sub-ocean
    - Depleted fossil fuel reservoirs
    - Enhanced oil recovery
    - Enhanced coal bed methane recovery
    - Other geological storage options
- Ocean Storage
- Combined capture and storage
    - Mineral carbonation
    - Industrial uses

Risk of leakage is a serious concern for CCS. Geologic storage is not expected to leak significantly over time; storage times are expected to be greater than 100,000 years. Any leakage that occurs would likely be through fissures in the cap rock or through abandoned wells.

Small leakages lead to less-effective sequestration and more climate change. Slow leaks can also work their way through the water table on the way to the surface, which can decrease its pH, causing environmental problems (Metz et al 2005, 34). At the surface, leaked CO_2 could accumulate in basements and cellars, causing asphyxiation.

A catastrophic release of CO_2 through a fissure or well could cause CO_2 to accumulate at the surface in concentrations high enough to kill humans and other animal life in the vicinity. An example of catastrophic CO_2 release, not related to human activity, is the Cameroon disaster of 1986. A cloud of CO_2 gas was released from the volcanic Lake Nyos, killing all animal life within a 25km radius, including more than 1,700 people. While this event was unrelated to CCS, it illustrates the seriousness of avoiding leakage. Asphyxiation can happen quickly, and without any major signs of danger.

To avert harmful leakages, monitoring, measurement, and verification processes will need to be implemented. Current technologies used involve 3D and 4D reflection seismology. Data are expensive to collect, and require highly-specialized, skilled workers, and months between iterations. Other monitoring techniques include tilt meters, passive source microseismic mapping, electrical resistance tomography (ERT), chemical tracers, soil chemistry studies, and deployment of atmospheric eddy correlation towers (Friedmann 2003, 6).

There are a few risk assessment tools that are being developed throughout the world. One is GEODISC from the CO_2 Capture Project in Australia. It has developed an ESSCI rating (Environmentally Sustainable Site for Carbon Dioxide Injection) that takes into account a number of factors. It warns, however, about using single number rating systems for two reasons. First, it is impossible to arrive at one number that is universally valid because of the diversity of subsurface conditions. Second, "if such a number is arrived at, people are likely to misuse it." (Bradshaw 2001, 171-3)

3.4.1 Geological Storage

Geological storage involves injecting compressed CO_2 into rock formations below the earth's surface. Usually, the sites proposed are at depths below 800m, where the pressures will keep CO_2 in a liquid or supercritical state.

The cap rock above the storage formation (shale and clay rock) forms an impermeable layer. Capillary forces can provide additional physical trapping within pores. If there are open sides to the formation, additional trapping mechanisms are necessary to ensure long-term storage of the CO_2.

Geochemical trapping is the reaction of CO_2 with the in situ fluids and host rock. CO_2 dissolves in the water. Then, over time, the dense CO_2 rich water sinks into the formation. The CO_2 reacts with the rock and forms solid carbonate minerals, over millions of years (Metz et. al. 2005, 31-32).

Saline. Saline storage occurs when CO_2 is injected into subterranean saltwater formations. The result is CO_2 saturated brine and liquid CO_2, which is less dense and will float above the solution. Saline storage reservoirs are prevalent, and the water is not suitable for agriculture or human consumption. The injection of CO_2 to displace the brine and extract geothermal energy has been considered, but most areas high in geothermal energy have more fissures in the rock, making them unsuitable for sequestration purposes (ibid. 2005, 217).

CO_2 at proposed storage depths of 800m will have a density 50% - 80% of that of water, so it will tend to float above the water. This makes a well-sealed cap rock very important. In oil and gas reservoirs, CO_2 can fill most of the space the displaced fluid took up. In saline reservoirs, however, CO_2 can only make use of up to 30% of the total rock volume. (ibid. 2005, 31)

Sub-Ocean. Geologic storage can also take place beneath the oceans. It has an advantage in the oceans' capability of absorbing small leaks over time and further delaying the release of CO_2 back into the atmosphere. Catastrophic release of CO_2 carries the same risks to local ecosystems as terrestrial storage, and only shifts the risk to marine ecosystems.

Depleted Fossil Fuel Reservoirs. Storage in depleted fossil fuel reservoirs refers to depleted natural gas and oil reservoirs.

Enhanced Oil Recovery. Enhanced oil recovery uses injected CO_2 to displace oil and force it out of wells. Once the oil has been recovered, the CO_2 can be sealed within the rock instead of vented to the atmosphere. This is being done in Texas, and is planned for the Weyburn project (ibid. 2005, 203-4 and 43).

Enhanced Coal Bed Methane Recovery. Enhanced Coal Bed Methane Recovery refers to the storage of CO_2 in coal beds to displace the methane that is already stored there. Coal deposits have fractures, called cleats. Between those cleats, solid coal has a lot of micropores, where gas molecules, that enter from the cleats, can be adsorbed. Coal can adsorb up to 25 normal m^3 (1 atm @ 0 ºC) of CH_4 per tonne at coal seam pressures. Coal has a higher affinity for CO_2 than CH_4 so injecting CO_2 can replace the methane and allow it to be recovered, while storing the CO_2. (ibid., 217)

The coal or organic-rich shales provide additional trapping of CO_2 as it is preferentially adsorbed onto the coal, replacing methane. The CO_2 will remain trapped as long as pressures and temperatures are stable. The coal bed methane storage is shallower than hydrocarbon and saline formations (ibid, 32).

Other Geological Storage Options. There are other geological formations that could potentially store CO_2 that have not been thoroughly studied yet. Some ideas include basalts, oil or gas shales, salt caverns, and abandoned mines. (ibid., 219). Mineral carbonation is another well-studied option that is covered later in this chapter.

Geologic ***Storage Potential*** *and Status*

Table 3.12. Geologic CO_2 storage capacity and retention time (Grimston et. al. 2001, 161)

Sink	**Capacity (Gt C)**	**Retention (years)**
Enhanced Oil Recovery	20-65	10s
Coal Bed Methane	80-260	>100,000
Depleted Oil/Gas	130-500	>100,000
Deep Aquifers (Saline)	Up to 14,000	>100,000

New experimental carbon sequestration fields are being created all the time. Following are some examples of the largest and most well-known fields being used to store carbon.

Sleipner Example:

Sub-ocean saline geologic storage is currently being demonstrated by the Sleipner project in Norway to rid excess CO_2 from natural gas being mined before it could be sold in Europe. The project started in 1996, and has been storing about 1MtC per year. that is extracted from the natural gas it extracts nearby. 20MtCO_2 expected to be stored over the lifetime. It has a very large storage capacity (1-10 Gt CO_2) (Metz et. al. 2005, 202).

Note that it would take 3,500 Sleipner projects to constitute a single stabilization wedge in Pacala and Socolow's strategy for stabilizing greenhouse gas emissions. (Pacala and Socolow 2004, 970).

Weyburn Example:

CCS is being used for enhanced oil recovery in the Weyburn project, straddling the United States-Canadian border in the Williston Basin. It is expected to inject 23 MtCO2 and extend the life of the oil field by 25 years. (Metz et. al. 2005, 203-204).

The CO_2 comes from a coal gasification plant in North Dakota (325 km away). Weyburn should accept 3,000-5,000 tonnes per day for the next 15 years. (ibid., 204).

Salah, Algeria Example (Enhanced Natural Gas recovery):

An enhanced natural gas project by Sonatrach, BP, and Statoil is being demonstrated in Salah, Algeria. It was created to use the extra CO_2 contained in the mined natural gas from the site (up to 10%) and re-inject it into the reservoir, aiding in the recovery of more natural gas (ibid., 203).

1.2 $MtCO_2$ will be stored annually in the reservoir, with a total of 17 MtCO2 stored over the project's lifetime (ibid., 203).

All geologic storage options are in compliance with the sustainability principles. They all help to reduce an existing SPI violation, and will be storing significantly more CO_2 than that which is emitted in the storage process. Enhanced oil recovery and coal bed methane storage receive a lower score because they are implemented to gain access to more fossil fuels, which further contributes to CO_2 emissions.

Table 3.13. Sustainability assessment for geologic CO_2 storage

Option	**SP Compliance**			
	I	**II**	**III**	**IV**
Saline	++	++	++	++
Sub-ocean	++	++	++	++
Depleted FF	++	++	++	++
EOR	0	++	++	++
ECBM	0	++	++	++

3.4.2 Ocean Storage

The oceans cover 70% of the earth's surface and total more than $1.37x10^{21}$ liters. Each day they absorb an estimated 20Mt of CO_2, or a total over more than 7 $GtCO_2$ (2GtC)/yr. (ibid., 282)

Oceans are estimated to contain fifty times the amount of carbon present in the atmosphere and roughly twenty times the amount of carbon contained in plants and soils. Since the start of the industrial revolution the oceans are estimated to have absorbed in excess of 500 $GtCO_2$ (out a total anthropogenic emissions of 1300 Gt). (ibid., 281)

The alkaline chemical capacity of the oceans will eventually absorb up to 85% of all fossil fuel CO_2 emissions to the atmosphere, or the equivalent of 4,500 billion tons of CO_2 could be accommodated with a pH change of about 0.3.(U.S DOE, 2001)

Thus oceans are more than capable of absorbing all anthropogenic carbon emissions for maximum forecast values for the next 100 years (reference) however, the potential effects on ocean chemistry are unknown and it seems unlikely that all species would be able to adapt to such short-term changes.

"About one-third of the carbon dioxide we emit (2 of 6 PC/yr) is being absorbed by ocean surface waters and mixed to the deep ocean, with unknown long-term effects." (Caldeira et al, U.S. DOE, 2001)

The two most frequently proposed methods for ocean sequestration are:

- fixed pipeline to sub-3000m ocean bottoms; and
- dispersal in the sub-1000m water column via a towed pipe attached to a moving ship.

It should be noted that for countries with poor geologic storage options and close proximity to deep oceans, like Japan, ocean storage presents a convenient sequestration option and it is thus not surprising that they continue to explore ocean sequestration potential.

Current experimental efforts: most recently two attempts at experimental releases of pure liquefied CO_2 (60 tons off Hawaii in 2001 and 5 tons off Norway in 2002) at 800m depths have been cancelled by governments because of stiff opposition from environmental groups and the public. (Metz et. al. 2005, 285)

Small-scale releases (less than 10L) have been performed at 1000 – 3000m depths to explore behaviour of CO_2 in situ.

The 1972 *Convention on the Prevention of Marine Pollution by Dumping of Waters and Other Matters* (usually known as 'the London Convention') prohibits dumping of industrial waste in the water column. At this point the status of CO_2 as an 'industrial waste' is unclear, however, given the current propensity for some states to flaunt international agreements if it is perceived to be in their economic interests, it is questionable how much deterrent effect the London Convention will have in the future.

"Adding CO_2 to the ocean or forming pools of liquid CO_2 in the ocean floor at an industrial scale will alter the local chemical environment. Experiments have shown that sustained high concentrations of CO_2 would cause mortality of ocean organisms. CO_2 effects on marine organisms will have ecosystem consequences. The chronic effects of direct CO_2 injection into the ocean on ecosystems over large ocean areas and long time scales have not yet been studied." (Metz et. al. 2005, 22)

Given that oceans are poorly understood (both in CO_2 chemistry and effects on marine organisms), especially over centuries, it would seem to suggest a very cautious approach to any serious changes to ocean CO_2 concentrations.

Table 3.14. Sustainability assessment for ocean CO_2 storage

Right Direction		
SP I	--	Directly leads to systematic increase of carbon in oceans.
SP II	+	CO_2 becomes carbonic acid when dissolved in water.
SP III	-	Pipelines and infrastructure. Local highly acidic regions.
SP IV	+	No significant violations.

3.4.3 Mineral Carbonation

Mineral carbonation is a special case as a carbon storage option, because it also includes the carbon capture phase. Carbon dioxide reacts to form stable mineral compounds that do not have to be stored in a confined space to avoid leakage back to the atmosphere.

Mineral carbonation occurs naturally in nature on a geological time scale and is known as silicate weathering. In this process CO_2 is sequestered from the atmosphere through the reaction of CO_2 with metal oxide bearing materials to form insoluble carbonates. Once this process has occurred there is virtually no leaking of CO_2 back into the atmosphere. This reaction can also be performed in a chemical processing plant in which either silicate rock or industrial wastes, such as fly ash, are combined with a CO_2 feed stock. The main components of this process are:

1. Preparation of the solid reactants, including mining, transport, grinding;
2. Processing of the carbonates, under controlled reaction parameters; and,
3. Disposal of the carbonates and by-products.

When CO_2 is combined with a metal oxide (indicated here as MO, where M is a divalent metal such as magnesium or calcium) a carbonate is formed according to the following exothermic reaction:

$$MO + CO_2 \rightarrow MCO_3 + \text{heat}$$

In general a large fraction of heat is released, however, with present technology there is always a net demand for high grade energy when the entire mineral carbonation process is considered.

The carbonate formed is between 50 and 100% by volume greater than that which was originally mined. As it is not cost effective to ship the bulk of these materials over great distances, processing plants would need to be located close to metal oxide sources. Mine reclamation would then also provide for a suitable disposal means. CO_2 feed stock and power would then need to be supplied to the process plant.

Silicate rocks are mainly found in geological zones where there has been a lifting of the earths crust. Estimates have indicated that there are sufficient Magnesium silicates alone to neutralize the CO_2 from all world wide coal resources. The mining of which would not differ substantially from other minerals with similar properties such as copper.

Table 3.15. Sustainability assessment for mineral carbonation CO_2 storage

Right Direction		
SP I	**0**	Silicate rocks contain chrysotile, a natural form of asbestos.
SP II	++	No significant violations.
SP III	-	Large Scale Mining required
SP IV	++	No significant violations

3.4.4 Industrial Uses

This section refers to reusing captured CO_2 in industrial processes that currently require CO_2.

CO_2 currently has a large number of industrial uses which include the production of chemicals (urea), refrigeration systems, horticulture and beverage carbonation. New process routes for the production of organic chemicals, primarily polyurethane and polycarbonates, are currently being investigated. In this application CO_2 is used in place of other carbon feed stocks such as methane or methanol.

In order to properly understand CO_2 sequestration in an industrial process, the system boundary must include all materials, fossil fuels, energy flows, emissions and products. To determine the overall effect on atmospheric mitigation the following three factors need to be considered.

1. Product lifetime
2. Source of CO_2 feedstock
3. Scale of operation

The product lifetime determines the duration CO_2 sequestration. This spans a broad range from several days in the case of beverage carbonation to centuries for polyurethanes. Most of the CO_2 used commercially is recovered from synthetic fertilizer and hydrogen plants. This is CO_2 that would otherwise be released to the atmosphere, so by replacing it with that captured from power generation plants will have no net effect on reducing atmospheric levels. A total of about 0.12 Gt CO_2 /yr are currently used for industrial purposes. This is equivalent to approximately 0.5% of all anthropogenic CO_2 emissions. A substantial expansion of the current chemical industry would need to be required in order for this to be considered a climate change mitigation strategy.

Table 3.16. Sustainability assessment for industrial uses of CO_2

Right Direction		
SP I	++	No significant violations.
SP II	-	Organic chemicals and polymers (polyurethane and polycarbonate)
SP III	++	No significant violations
SP IV	++	No significant violations

3.5 Desired Future (C1 Step)

This section covers the first part of the C step in the ABCD process: creating a vision for the future. The second part of the C step, developing strategies for success, is covered in subsequent sections.

Ideas for a sustainable stationary power sector within society within the biosphere were generated during brainstorming sessions as well as from the research performed during the course of this thesis. These ideas were grouped together and refined in order to help develop a shared mental model of a desired future. This desired future represents just one possible vision of a stationary power sector that complies with the sustainability principles, the main characteristics of which are listed below:

1. Energy efficiency is a primary design consideration throughout the stationary power sector and all processes are designed to minimise power consumption.
2. A diversified blend of renewable power technologies determined by local natural resources, is connected to a common power network.
3. Urban centers are internally linked as well as connected to neighbouring networks to help ensure power supply resilience.

4. Electricity generated from stored energy sources such as hydrogen or water from high reservoirs, is used to help compensate for shortages caused by peak demand and renewable power supply fluctuations.
5. Energy security and local economic development are enhanced by encouraging locally-owned and locally-operated power technologies.
6. Biomass and geothermal power stations where possible, are located close to communities in order to provide heating services as well as electricity (cogeneration).
7. Biomass power stations are equipped with CCS in order to help restore atmospheric CO_2 concentrations to within pre-industrial variations.
8. Power generation does not produce highly persistent toxins that cannot be broken down by biological processes (current nuclear technologies are not acceptable).
9. Community residents have a systems perspective of the stationary power sector and act responsibly in order to preserve its integrity.

Figure 2 illustrates how these ideas could be incorporated into a stationary power sector. This graphic helped strengthen our shared understanding of the desired future and provided a clear point from which to backcast.

In this desired future community, there are power supply contributions from a variety of different natural resources (wind, solar, biomass, etc). These contributions are all networked together and joined with the neighbouring community. Residents in this community play an active role in both reducing the amount of electricity they consume (ground source heat pumps, passive solar design, etc) and in increasing the amount of electricity they supply (photovoltaics and micro wind power generation). Cogeneration is used at the nearby geothermal power station in order to supply the community with both power and district heating (heating for radiators and hot water tanks). The biomass power station is implementing carbon capture technologies and is actively reducing atmospheric CO_2 concentrations.

Overall, the stationary power network is designed to be resilient and flexible such that advances in technology and changes in demand can easily be incorporated. This community also enjoys a more peaceful and healthy lifestyle as there is no more geo-political tension or pollutants in the air and ground water from the use of fossil fuels.

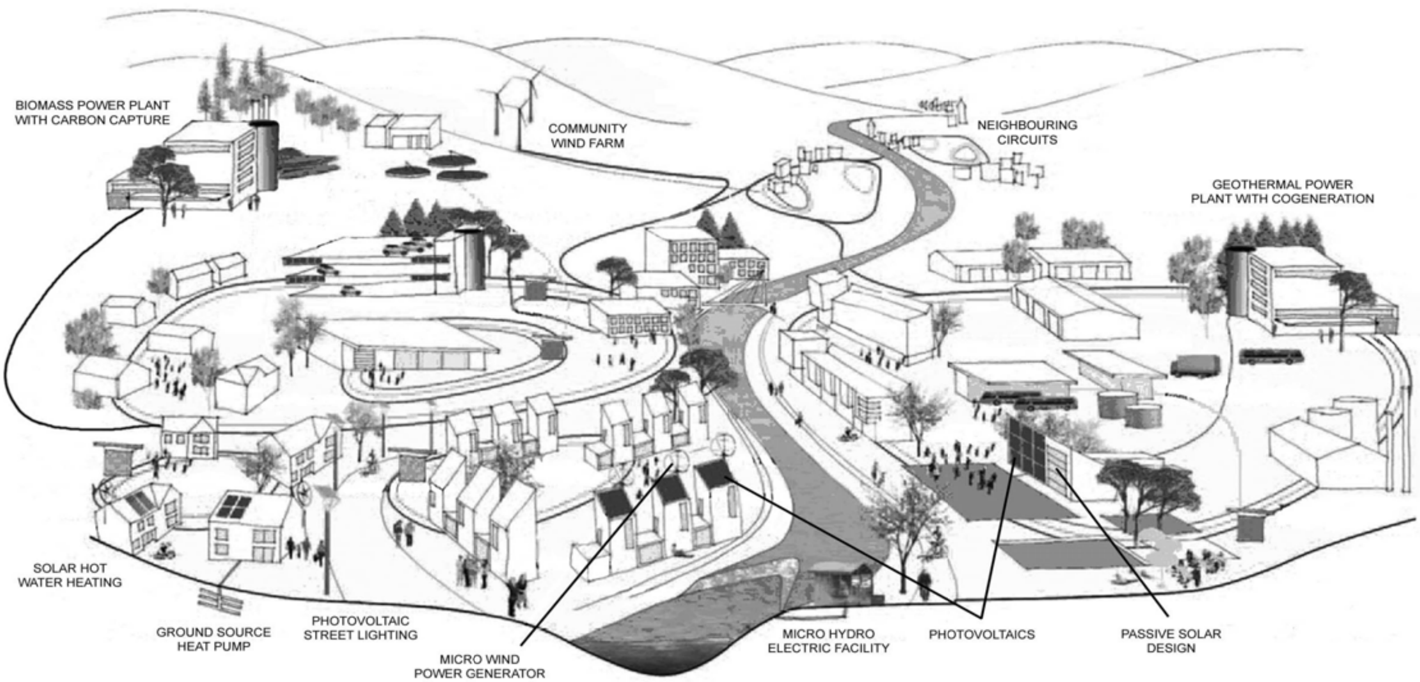

Figure 3.3. Stationary power sector "Desired Future" (adapted from Greenpeace 2006, 21)

3.6 Strategies for Success (C2 Step)

The second part of the C Step involves developing strategies for success. It coincides with Level 3 of the 5-Level framework for Strategic Sustainable Development. Measures from the B step are clustered together into three main groups:

1. Total supply reduction through demand reduction (dematerialization)
2. Change the mix of supply towards renewable energy (substitution)
3. Carbon capture and storage of CO_2 emissions (abatement)

3.6.1 Demand Reduction

Demand reduction is represented by actor 'm' on the CLD (Figure 3.1), and is a key leverage point because it strengthens balancing loop B2 by reducing power consumption. Stakeholder awareness and sustainable policy are required to engage this leverage point.

Traditional thinking on power generation has focussed on increasing supply to match increasing demand, which was assumed to be an essential contributor to increasing prosperity. More recently it has become apparent that improving energy efficiency (or "demand reduction") can maintain the same or improved levels of energy services while using less energy per unit of goods and services. Explorations of the full potential for efficiency measures have just begun and already there is strong evidence that efficiency improvements could be the single most important strategy for the reduction of power-related CO_2 emissions (IEA 2004, 35).

A full appreciation of the potential for reducing CO_2 emissions with efficiency requires systems thinking – in this case one action towards sustainability can have one or more additional positive spin-offs that multiply progress towards success. For example, improving lighting efficiency combined with enhanced natural daylight usage reduces electricity consumption, which reduces CO_2 emissions and reduces operating costs. However, there is more; lighting-related heating now declines, which reduces the amount of air-conditioning equipment required, which reduces CO_2 emissions and the capital and operating costs. In addition, natural daylighting has also been shown to improve employee productivity and employee satisfaction which reduces labour costs and labour turnover (Kats 2003, 6). There are also employment benefits associated with demand reduction over increasing supply; saving electricity produces more local employment at a broad range of skill levels spread across a variety of small businesses.

A second factor relevant to the success of efficiency measures in reducing CO_2 emissions is the relative contribution of fossil fuel generation in the supply mix; the higher the fossil fuel contribution, the greater the reduction in emissions from a reduction in end usage. This is not to say that areas with low fossil fuel power generation (for example, Norway or Quebec with large hydroelectric generation) cannot benefit from efficiency; their renewable power can be exported to their neighbours.

Compared with other strategies mentioned in this study efficiency measures are more varied and complex and subsequently more difficult to assess in terms of their potential. An additional challenge is that efficiency has often been overlooked as a method for increasing electricity service provision. Instead, utilities and governments tend to focus predominantly on increasing supply.

Experience seems to indicate that efficiency measures can produce rapid and significant reductions in end-use power consumption when there is a clear and compelling need coupled with determined government policies.

In 2001 California experienced average electricity prices of $0.35/KWh – a ten-fold increase over six months. In response the state was able to reduce average electricity consumption by 8% in one year. One-third of residential customers reduced their demand by more than 20 percent; meanwhile the economy grew by 2.3%. These efficiencies were achieved at an average cost of $0.03/KWh (Bachrach et al 2003, 5). "Thanks to energy efficiency standards that California has imposed on its own power industry, buildings, and appliances over the last 30 years – and its increasing reliance on renewable energy sources – California today consumes a little more than half as many kilo-watt-hours of energy per capita each year as the rest of America." (Friedman 2006)

Examining energy intensity change over time Rosenfeld et al from the California Climate Commission have noted: “world energy intensity (E/GWP) is spontaneously dropping 1.3% per year” (Rosenfeld et al, 2004, 373).

This decline has occurred during a time when large fossil fuel generation and nuclear were subsidised and efficiency encouragement was minimal. If a levelised price, that reflected the true cost to society and the environment, was charged for electricity and efficiency was actively encouraged it seems reasonable to expect that energy intensity reductions could be maintained at a level below that of primary energy consumption growth. In doing so we could experience a growing economy at the same time as our net energy consumption declines.

3.6.2 Renewable Energy

Society will always have energy needs. In a sustainable society, it is important that that energy production does not violate the Sustainability Principles, and that the energy comes from renewable sources.

Thus, only the power generation options from the B step that fit those criteria are considered here. Fossil fuels fail the test due to their CO_2 emissions. Nuclear is also not considered due to the radioactive waste. Large scale hydroelectric power is left out of consideration because of the effects it has on fish populations and the flooding it causes.

The technologies that are still being considered in this category are wind, PV solar, small- and medium-scale hydro power, ocean power (waves, tides, and currents), and biomass.

This strategy is represented by actor ‘n’ in the causal loop diagram (Figure 3.1), and is a leverage point because it strengthens balancing loop B3 by reducing fossil fuel power consumed. Sustainable policy and stakeholder awareness will be required to engage this leverage point.

3.6.3 Carbon Capture and Storage

This section evaluates the third set of measures from Section 3.5: Carbon Capture and Storage (CCS) technologies.

Carbon capture and storage helps reduce the impact of CO_2 emissions from fossil fuel consumption. It corresponds to actor 'O' in the CLD (Figure 3.1). Sustainable policy measures are required to engage this leverage point.

Only those measures that passed the sustainability assessment in the B step are considered within this strategy. For carbon capture, that means membranes and cryogenics are acceptable, but not amines. For the storage phase, geologic storage methods are considered, but not ocean storage.

Storage Potential

Geologic storage space is more than sufficient for any amount of CCS we choose to implement. The greatest amount of storage is in deep saline aquifers. Pacala & Socolow (2004, 969) estimate the total anthropogenic carbon emissions over the next 50 years (from 2004 until 2054) in a business as usual scenario. The scenario starts with 7 GtC of emissions and ends with 21 GtC. The total emitted carbon in this scenario is 550 Gt. From Table 3.17, below, we can see that deep aquifers can hold that amount of carbon 25 times over. Not all emitted carbon would need to be stored, as there are other carbon sinks, such as the oceans. With that in mind, depleted oil and gas reservoirs could even store all excess anthropogenic CO_2 for the next 50 years.

Enhanced Oil Recovery (EOR) and Enhanced Coal Bed Methane (ECBM) have lower capacities, and are used to extract extra fossil fuels for burning – leading to more carbon emitted to the atmosphere. This makes them a step in the wrong direction and not a flexible platform for future development. These two methods initially appear very appealing financially, as the recovered fossil fuels can be sold and the operation will generate income rather than cost money.

Table 3.17. Geologic storage options comparison

Sink	**Capacity (Gt C)**[5]	**Retention (years)**[6]	**Flexible platform**	**Cost of storage $ per tonne.**[7]
Enhanced Oil Recovery (EOR)	20-65	10s	No	(10-16)
Coal Bed Methane (ECBM)	80-260	>100,000	No	(10-16)
Depleted Oil/Gas	130-500	>100,000	Yes	0.1-0.3
Deep Saline Aquifers, including sub-ocean	Up to 14,000	>100,000	Yes	0.1-0.3

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[5] (Grimston et. al. 2001, 161)

[6] Ibid.

[7] (Metz et al. 2005, 345). EOR and ECBM indicate a profit of $10-16 per ton of CO_2 stored.

4 Discussion

4.1 Overview

As a starting point in this analysis, it was assumed that the energy supply mix will necessarily change over the long term due to the need to address climate change and price pressures associated with fossil fuel availability. Furthermore, 'success' was defined as 1) compliance with SSD sustainability principles I-IV, and 2) that CO_2 concentrations would peak around 500 ppm then trend back towards 280 ppm as a result of specific actions taken to reduce emissions.

The energy generation and CCS technologies presented in the Results section were analyzed on the basis of the sustainability principles and other key metrics. Technology options that did not conform to the sustainability principles were eliminated from consideration in the C step of the ABCD analysis. In this section, the D step of the ABCD analysis will be presented, and selected actions will be prioritised by answering three key questions:

1. Does this measure proceed in the right direction with respect to all of the sustainability principles?
2. Does this measure provide a flexible platform for further development?
3. Is this measure likely to produce a sufficient return on investment?

In addition, two other prioritisation schemes for energy supply transition were identified through a literature search, and are presented in this section.

The traditional approach to meeting increasing power demand has been to increase power generation capacity. More recently it has become apparent that improving energy efficiency (or "demand reduction") can maintain the same or improved levels of energy services while using less energy per unit of goods and services. Explorations of the full potential for efficiency measures have just begun and already there is strong evidence that efficiency improvements could be the single most important strategy for the reduction of power-related CO_2 emissions (IEA 2004, 35).

The optimal strategy may first require a shift in thinking to acknowledge that what people want from the power industry is *the services power provides*, not the vector for that power (electricity). On a unit of energy basis, decreasing power demand is equivalent to increasing power generation supply. Even when including the full costs and benefits of a power supply, demand reduction is more economical and can have numerous additional positive results that reduce or eliminate sustainability principle violations. Some of the benefits of a decentralised, sustainable power system include: increased employment, reduced pollution emissions, improved local air quality, improved energy security and enhanced local economic activity.

Current power prices do not reflect the full costs because they do not include the cost to the environment and society of Sustainability Principle violations. Current prices also appear to be artificially low because of the wide variety and scale of financial and regulatory subsidies for unsustainable power options. Although there has been some subsidisation of more sustainable power sectors, fossil fuels and nuclear power have been the beneficiaries of signification subsidies. Building the full costs into the retail power price is an excellent monetary method to communicate the relative costs of power to end-users. Of course significant increases in power costs will be greeted unfavourably by society unless governments package the policies with clear and simultaneous offsetting benefits, for example investing fossil fuel tax money in improved and affordable public transit.

Even taking the most pessimistic cost projections for reaching success, business as usual is very likely to cost far more in the long run. Although it is very difficult to clearly establish cause and effect between CO_2 emissions and climatic disasters, economic losses due to extreme weather events have run into hundreds of billions of dollars. In light of our research we contend that the cost of achieving success over the next century reduces global income by a negligible fraction while conferring significant non-monetary benefits (Azar and Schneider 2002).

Once the three main strategies are analyzed, further discussion of the results is placed in the context of the research questions at the end of this section.

4.2 D Step

The final step of the ABCD process entails a comparison of potential measures to determine whether they are moving in the right direction with respect to sustainability principles, whether they are likely to be flexible platforms for future development, and whether investments are likely to produce a sufficient return on investment. Table 4.1 shows a comparison of the three strategies identified by the CLD analysis, which have the effect of reducing CO_2 emissions produced by fossil fuels. The results are organized according to demand reduction, power generation technologies and the addition of CCS to fossil fuel power generation.

4.2.1 Demand Reduction

Demand reduction is a powerful strategy for assisting society to move in the direction of a sustainable power sector (illustrated in Appendix D: Computer Model Results – Demand Reduction Scenario). In fact, demand reduction does more than take society in the right direction; it takes us to our destination because the most sustainable power is power we did not need to generate. The process of reducing demand also has multiple associated sustainability benefits like improved building habitability and enhanced local economic resilience. Demand reduction is a highly flexible platform because: firstly, it can be performed incrementally, over time, as budgets permit. Secondly, it can be actions on a very small scale (changing a light bulb) to very large (installing co-generation on a power plant) and thirdly, it can be enacted by anyone, anytime, in any region. Efficiency measures are of particular value in the developing world, where electrification infrastructure investments are being made on a large scale, often for the first time. It is much more economic for developing nations to invest in the most efficient end-use designs and equipment available because it greatly reduces their need to invest in expensive generating capacity and the accompanying locked-in fuel requirements. Amory Lovins states: "highly efficient use of electricity, far from being a luxury of the rich, is a necessity especially of the poor." (Lovins and Gadgil, 1991)

Assessing the return on investment for demand reduction is made very difficult since this strategy involves a wide variety of actions, often applied in concert, in complex systems like factories or buildings.

Table 4.1. Comparison of some examples of demand reduction actions

Energy Efficiency Improvements	SP I	SP II	SP III	SP IV	Flex. Plat	ROI
High Efficiency Industrial Motors	+	+	++	++	Yes	Very short
High Efficiency lighting	+	+	++	++	Yes	Short
Daylighting	++	++	++	++	Yes	Short to long
Heating, Ventilation and Air Conditioning (HVAC)	+	+	++	++	Yes	Short
Solar Hot Water Heaters	++	++	++	++	Yes	Medium
Heat Pumps	+	+	++	++	Yes	Long
Building Insulation	+	++	++	++	Yes	Short to long (goals, retrofit vs. new build)
High Efficiency Appliances	+	+	++	++	No	Short to medium

In this table we offer some examples of efficiency activities, recognising that there are a wide range of appropriate actions that are available to each sector in each location. Estimating the cost of efficiency on a $/KWh basis is not a comprehensively-studied science and developing individual life cycle analyses for the strategies listed is beyond the scope of this paper however, previously-mentioned research indicates efficiency costs of 0.03 – 0.05/kWh are not uncommon.

Table 4.2. Strategies for a sustainable stationary power sector

Sustainable Power Strategy	SPI	SPII	SPIII	SPIV	Right Direction	Flexible Platform	ROI Payback Time (short, med, long)	ROI Cost of CO_2 Abetment (low, med, high)	Time to Commercialization (years)	Notes
Demand Reduction										
Improved Efficiency	++	++	++	++	Y	Y	S/M/L	L/M/H	0	Applicable anywhere, often low-tech
Renewable Power										
PV	+	+	+	+	Y	Y	M/L	H	0	Applicable to non-grid connected societies
Wind	+	+	++	++	Y	Y	M	M	0	Applicable to non-grid connected societies
Hydroelectric (micro)	++	++	++	++	Y	Y	M/L	L/M	0	Large opportunities already exploited
Ocean	+	+	++	++	Y	Y	M/L	M/H	5-10	
Biomass	+	++	+	+	Y	Y	M	L/M	0	Carbon neutral
Biomass w/CCS	++	++	+	+	Y	Y	M/L	M/H	5-10	Possibility of atmospheric CO_2 removal.
Geothermal	+	++	++	++	Y	Y	M/L	L/M	0	Not widely available
Fossil Fuel Power with CCS										
IGCC w/CCS	0	0	0	0	Y	Y	L	H	10-15	
PCC w/CCS	0	0	0	0	Y	Y	L	H	10-15	

We would like to close this section with a quote from the David Suzuki foundation: "The energy productivity resource is purely renewable, and its size is limited only by human ingenuity." (Suzuki Foundation, 2002)

4.2.2 Renewable Power

Based on the definition of 'success' created for this study, it is clear that wind, photovoltaic, hydroelectric, ocean (wave/tide), biomass and geothermal are steps in the right direction, according to the sustainability principles, and also have the effect of decarbonising the energy supply (illustrated in Appendix D: Computer Model Results – Non-fossil Fuel Scenario). They are flexible platforms for future development though they generally have a medium to long term payback period. One important factor is that the bulk of the investment in these technologies is front-loaded as a capital investment. Once the infrastructure is operational, there are no operating costs associated with fuel, with the exception of biomass, which would require harvesting and transport of biomass to the power generating facility.

The cost of decarbonising the power supply mix varies depending on the total amount and type of fossil fuel currently used. It also depends on the renewable energy technology selected, and the locally available renewable resources. Solar is more expensive than wind or hydroelectric for a given energy production capacity, for example.

Timing to commercialization also varies. Wind, PV, and hydroelectric have been commercialized and are widely deployed around the world. Geothermal power is not as widely available simply due to limited availability of high quality heat sources that are geographically accessible. Ocean power is a relatively new frontier, with a few pilot scale plants in operation worldwide.

Biomass power generation is also deployed at a moderate level, but a great deal of effort in this area is currently resulting in capacity growth, particularly in Europe. Many existing coal-fired power plants can be operated with biomass exclusively, or mixed with coal, which enables the existing infrastructure to be a flexible platform. The combination of biomass with CCS is another exciting prospect for utilizing infrastructure designed for fossil fuels, but substituting a renewable fuel. In this particular case however, something entirely new is possible – the ability to remove net CO_2 from the atmosphere (Azar et al. 2006). This is possible because as the biomass grows, it takes up CO_2 via photosynthesis and converts it into plant matter. When it is burned for power, the CO_2 which would be re-released to the atmosphere is instead captured and stored underground.

4.2.3 Fossil Fuel Power with CCS

Economically, the CCS options are less favourable, and this underscores the role that sustainable policy-making can have in levelling the playing field and allowing theses technologies to become competitive by removing subsidies and implementing penalties for carbon emissions.

Carbon Capture. Of the three carbon capture technologies assessed, membrane separation appears to be the most promising method. This is an emerging technology which has been demonstrated successfully at pilot and small scale operations, and the specific details with regards to the materials of construction and lifetime of operation are yet to be determined.

Although there were no major sustainability principle violation noted for cryogenic distillation, it is significantly energy intensive. This technology has the potential to operate at near 100% capture efficiencies, however, the energy requirement is a major strike against choosing cryogenic distillation for wide deployment.

Separation with sorbents was the least sustainable option. This is primarily because sorbents used for separation, notably amines, have known harmful effects on the biosphere, and due to the large quantities required there is a potential for accumulation.

Transportation and Storage. The common methods for transportation of CO_2 are tanker ship, rail or road tanker and pipeline. Of these options, pipeline was the lowest cost option, the least energy intensive and had the lowest risk of catastrophic leakage.

Our research on carbon storage revealed several main approaches currently being considered for the stationary power sector. In addition to the sustainability principles, both the quantity of CO_2 stored and duration of storage was considered for each approach.

Geological storage, in which the CO_2 is injected back into depleted gas reservoirs, was the most sustainable option. Experience with current geologic injection sites in Weyburn, Saskatchewan and the Sleipner field off the coast of Norway indicate that CO_2 can be stored safely and that there is no leakage. However, the leakage monitoring data from these sites is still less than a decade old and close monitoring over time should continue in order to build confidence in this option for the long-term. No additional sustainability violations were indicated for this method. Geological survey information suggests that there is a sufficient amount of suitable storage reservoirs for 50 years of stationary power emissions at our current rate of generation (IEA 2001).

All forms of ocean storage were unacceptable given the toxicity of localised high levels of CO_2 that ocean dumping would entail and the uncertainties regarding the long term stability and solubility of CO_2 at the pressures and temperatures anticipated in the ocean storage option.

Mineral carbonation is an attractive option in terms of 'locking' the CO_2 almost indefinitely, but there would be sustainability principle violations associated with large scale mining. Therefore this storage option is not proposed as part of a sustainable scenario.

4.2.4 Primary research question

In order to answer the primary research question, "*can point source carbon, notwithstanding fuel source, be sequestered in a sustainable manner*?," both carbon capture and storage were assessed independently of one another through the lens of the sustainability principles.

Our research supports our hypothesis that CCS can theoretically be operated sustainably, and that it can serve as a flexible platform for mitigating CO_2 emissions during the transition from a fossil fuel-based power sector to a sustainable power sector, with the following preferences for technology selection:

- Gas separation: Membranes are the preferred separations technology rather than amines or cryogenic distillation. Both have a high energy requirement, and disposal of amines represents a difficult challenge.
- Transportation: Pipeline is the preferred method over truck, rail or ship, due to fossil fuel consumption.
- Storage: Geological storage in saline reservoirs has acceptably low risks of leakage and is preferred over other variations of geological storage ocean or chemical storage.

4.2.5 Second Research Question

Now having shown that CCS can theoretically operate without Sustainability Principle violations, the second research question asks "*will investments in fossil fuel-based CCS be a strategic step towards a sustainable stationary power sector?*"

Adding CCS to power large scale fossil-fuel power generation adds significantly to the cost of constructing and operating a power plant. Installing CCS at a significant percentage of power plants around the world would require investments in the order of hundreds of billions of dollars. Given that such investments would automatically mean less resources available for investments in the parallel strategies of demand reduction and renewable power generation (and vice versa) it is essential to conduct a careful analysis on the basis of cost effectiveness and a sound long-term strategy in order to determine whether or not significant investments in CCS will be the most efficient and sensible way to achieve 'success.'

We will begin by examining the results of SSD prioritisation analysis for this technology. Referring to **Error! Reference source not found.** we see that fossil fuel-based CCS does help us move in the direction of our goal of reducing power generation-related CO_2 emissions in that it reduces CO_2 emissions per kWh by up to 90%.

CCS can serve as a flexible platform for mitigating CO_2 emissions during the transition from a fossil fuel-based power sector to a sustainable power sector, because it first decouples CO_2 emissions from coal-burning, and secondly it offers the potential of using existing infrastructure to both generate power and remove net CO_2 from the atmosphere if the fuel is switched to biomass. CCS technology can also be considered flexible in that it can be applied to other large point-source CO_2 emitters such as smelters and cement plants, sources of CO_2 emissions which are currently otherwise impossible to address. In doing so, CCS could prove to be an effective tool in the pursuit of decreasing atmospheric CO_2 levels to pre-industrial levels.

If the power plant in question were to continue burning coal with CCS, there may be some acceptable trade-offs over the short term with other violations of sustainability principles, such as mining damage to local environments, given the global need to stabilize the climate and meet energy needs simultaneously. Technologies exist today which can remove mercury from coal plant exhaust gases, and improved technologies are in the research and development stages. Requiring coal-fired power producers to utilize mercury abatement technology is a policy issue that should be addressed with some urgency everywhere coal is currently in use today.

Fuel switching from coal to biomass requires a separate analysis of the biomass potential at the regional and local level in conjunction with the other assessments. The source and harvest rate of the biomass must also conform to sustainability principles in order for this to be a sustainable option.

However, for CCS to be economically competitive there would need to be appropriate financial penalties for large point source CO_2 emissions such as a carbon tax or cap and trade system (illustrated in Appendix D: Computer Model Results – CCS Scenario).

Ideally, societies could phase out fossil fuel-generated power while successfully meeting demand through the development of sustainable renewable power generation and demand reduction. However, given society's dependence on the significant installed base of fossil fuel-fired (especially coal) stationary power and the enormous sunk investment that this infrastructure represents, it is understandable that they will be unwilling to abandon these investments prematurely. For some societies, CCS may represent a less expensive bridging technology than large-scale short-term adoption of other identified sustainable options.

Investments in fossil fuel-based CCS could be a strategic step towards a sustainable stationary power sector under the following circumstances:

1. After a society has already invested in demand reduction and is operating at high efficiency

2. When said society has large reserves of coal and a large existing investment in, and dependence upon, coal-fired power plants

3. When developing local renewable power, or importing renewable power from neighbours, is significantly more expensive than installing CCS technology. If all three of these conditions apply then it would appear that investments in CCS technology would be a strategic step towards a sustainable stationary power sector.

4. We cannot ignore the very real possibility that runaway climate change may force societies to invest in all means at our disposal in order to reduce CO_2 emissions, even if these investments are not necessarily the optimal strategies for a sustainable stationary power sector.

4.2.6 Third Research Question

Our final research question was: "What should governmental policy-makers take into consideration in order to develop sustainable strategies within the stationary power sector?"

Our findings indicate that there is no single correct answer to the question of, what society should do to move towards sustainable stationary power future. The power system is complex and each location will have unique resources, usage patterns, levels of development, needs, challenges and distribution networks that will need to be taken into account in order to select the optimal mix of power generation and/or CO_2 abatement technologies that will lead to success.

The information summarised in **Error! Reference source not found.** supports our hypothesis that the first strategy to be implemented should be demand reduction. These measures generally have a good return on investment in a short- to medium-term time frame. The renewable options are in alignment with the sustainability principles, and have varying return on investment. The fossil fuels with CCS do present some tradeoffs related to mining, and heavy metals which must be recognized. It is possible that in the short term, these trade-offs may be tolerated, but in order to be sustainable in the long term, these issues would have to be addressed through abatement technology, or fuel switching to biomass to avoid the violations. Further, these options are all flexible platforms, but they have varying ROIs.

Making further prioritizations is difficult, particularly when ranking the importance of ROI relative to other success factors, such as sustainability principle ranking and amount of CO_2 which can be eliminated. These priorities will necessarily have to be defined for the specific region and application to address the goals of the stakeholders and policy-makers.

Our research has identified two prioritisation schemes that are specific to developing strategies and making decisions about power sector infrastructure. Despite the difficult of balancing the tradeoffs, these ranking schemes constitute a sensible "order of operations" for making any changes to the system.

The first scheme is California's "loading order." California's Energy Action Plan (State of California) strongly supports the loading order that sets the priority for actions to meet increasing energy needs. (State of California 2005, 3)

1) Cost effective efficiency and demand response.
2) Renewable sources of power and distributed generation, such as combined heat and power applications.
3) Clean and efficient fossil fuel fired generation.

Another plan for approaching the problem has been developed by the Energy Research Centre of the Netherlands' Energy Efficiency in Industry (EEI) research unit. It has a 3-step prioritization plan it calls the Trias Energetica:

1) Efficiency: reduce demand to an intelligent minimum, by increasing efficiencies.
2) Renewables: apply renewables to the extent possible;
3) Clean fossils: for the remainder: use fossil fuels as clean as possible. (UNDP 2004, 13)

In both prioritisation schemes, demand reduction is the first action, an upstream solution to emissions problems. This can be a combination of efficiency targets, which could include incentives to purchase efficient appliances, or subsidies for home insulation, for example. The second action in the prioritisation schemes has the effect of decarbonising the power mix by replacing fossil fuels with renewable sources of energy. Finally, once the first two options have been considered, the last action is to make investments in using fossil fuels as efficiently and cleanly as possible. Improving the efficiency of the power plant or adding CCS technology to fossil-generated power are examples of this. This is not to say that all three strategic actions should not be examined and applied in parallel; indeed, given the magnitude of the challenge humanity now faces it is likely that all three will need to be applied at a large scale and in a short period of time if we are to meet our goals for success (illustrated in Appendix D: Computer Model Results – SSD Scenario). However, we should point out that improving fossil fuel technologies does not bring them into compliance with the sustainability principles or address their finite nature, and therefore CCS should be considered a bridging technology while society shifts to renewable, non-polluting sources of energy.

Policy Approaches. From our CLD we identified "sustainable governance" as the major leverage point, which is policy, public awareness and sustainable power policy. Power sector policy is a huge area of research and far beyond the scope of this study to fully examine the options in any detail. We have presented examples of government policy when describing our strategies for achieving our desired future in our results section. We will now briefly describe two policies identified through our research for encouraging demand reduction and sustainable power supply encountered in our literature review. In this discourse we are necessarily assuming that decision-makers are competent, and committed to a sustainable power sector and are able to communicate their commitment to all stakeholders (Robèrt et. al. 2005, 197).

Public Awareness

- Actively providing information underlining the connection between power usage choices and climate change and why involvement in international agreements is necessary. Actively engaging the public in a transparent, high profile, national and international multi-stakeholder dialogue. Mobilising public commitment to rise to the challenge.

- Clear information on the climate change issue, costs, benefits of transitioning.

- Mandatory labelling of fuel consumption and emissions for products (power efficiency of appliances, embodied CO_2).

- Encouraging educational institutions to include climate change studies into their curriculum.

General Policies for Sustainable Power (including demand reduction, generation and CCS):

- Introducing price mechanisms to increase energy prices

  – Removing subsidies and/or incorporate environmental externalities (violations of sustainability principles) so that fuel costs more accurately reflect the full costs. Passing costs on to the end-user and transparently redistributing tax proceeds towards sustainable alternatives.

  – Implementing revenue-neutral tax on power sector carbon fuels appropriate to the carbon content, with the proceeds being transparently applied to carbon-free generation options and demand reduction.

  – Alternatively, introducing a cap and trade system for large-scale emitters. Setting clear, binding emission reduction targets for all large CO_2 emitters with a locked-in timetable for future lower targets

- R&D for next generation technologies

  – Supporting proven sustainable technologies on the widest appropriate scale

- Supporting the development of new breakthrough technologies, accelerating deployment

- Establishing power consumption standards that encourage innovation towards efficiency for appliances, electrical goods and buildings

  - Establishing and enforcing legal standards for equipment and building codes

  - Encouraging dematerialisation

  - Promoting a "rethink, reduce, reuse, recycle" strategy to reduce overall energy consumption.

General Considerations for effectiveness:

1) Focus – Given the importance of reducing carbon emissions, policies should be measured in terms of their effects on CO_2 reduction and mitigation

2) Time - Policies must be phased in over an appropriate time frame so that society can adapt in an orderly fashion with minimal economic dislocation.

3) Transparency – Policies should be fully explained as to their intent, costs and where and how any generated revenue will be allocated.

4) Revenue Neutrality – policies should avoid resulting in an increase in electricity price for a given level of electricity services.

5) Subsidies - should be short-term (so as to avoid building dependency) and as available to a broad range actions that have a demonstrated ability, or high probability, of achieving success (so as to avoid accusations of favouritism).

6) Monitoring – suitable measurement tools must be employed to monitor the effectiveness of policies for achieving power sector sustainability. (Robèrt et. al. 2005, 196)

We recommend that decision-makers follow the generic methodology presented in the following flow diagram (Figure 4.1) to develop an individual strategic plan for moving their society towards a sustainable stationary power sector.

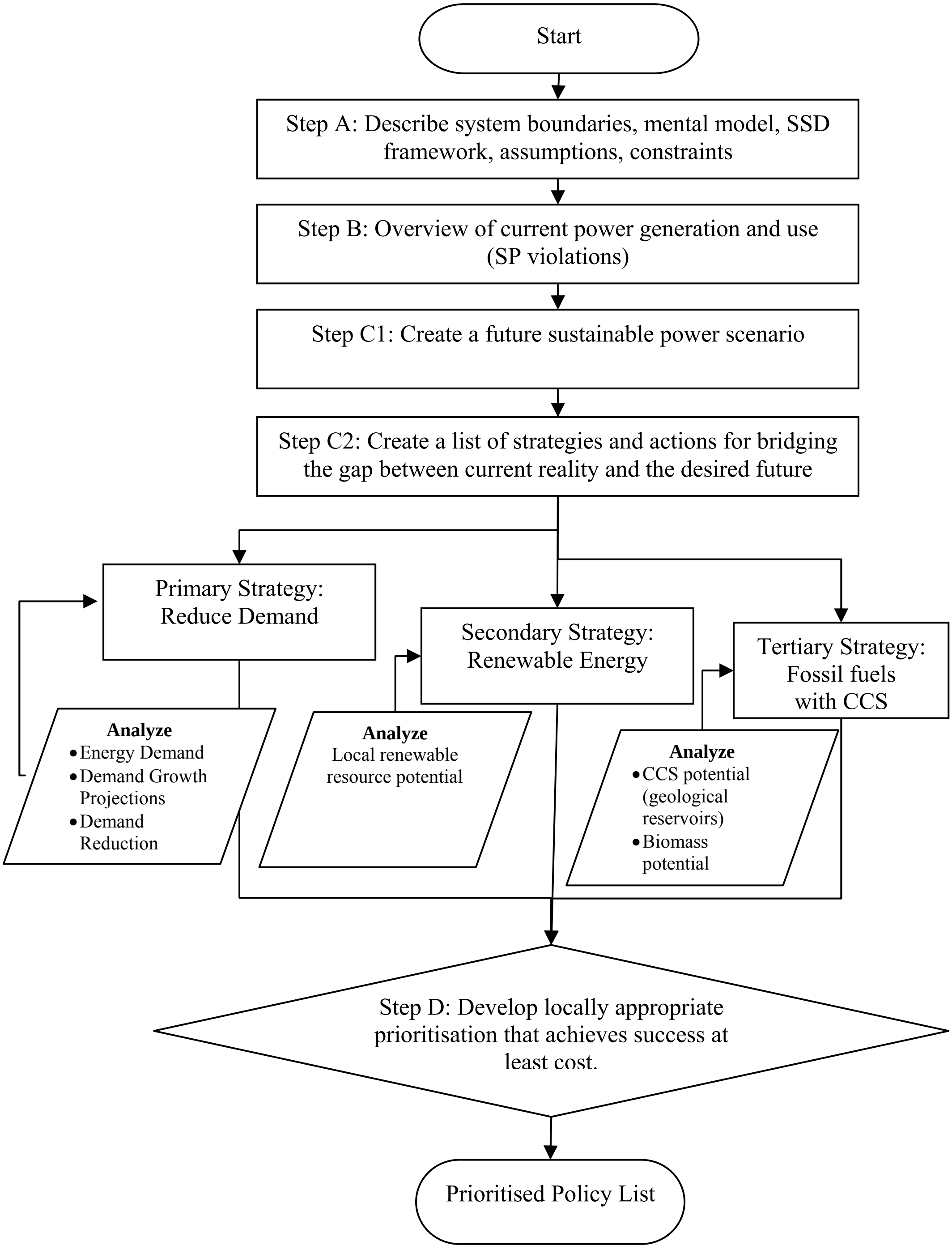

Figure 4.1. Decision-making process flow chart

5 Conclusions

In conclusion, this study has shown that point source carbon can be captured and stored in a sustainable manner. The preferred technology for separation of CO_2 from the effluent gas stream is gas separating membranes. In the short term, amine separation is the most economical approach, but the large quantities of amines present health hazards and disposal issues. The industry should transition to membrane separation technology for the long-term, in order to meet sustainability principles for the separation stage of the CCS process. Research suggests that geological storage of CO_2 can be done sustainably, particularly if sub-ocean geological reservoirs are used, because in the event of leakage, the escaped CO_2 will exist in the form of solids which are stable at the high pressures and low temperatures found on the ocean floor. Recognizing that it will not always be possible to utilize sub-ocean geological storage, terrestrial geological storage is the next best option. Mineral storage may be required ultimately, if there is not enough space in geological reservoirs, but in the near term, it is costly and cumbersome, requiring the transport of large quantities of mined minerals.

Carbon capture and storage is a flexible platform, because if the fuel is switched to biomass rather than coal, it enables for the first time, an effective approach to removing CO_2 from the atmosphere. This is possible because the biomass acquired CO_2 from the atmosphere during its growth through photosynthesis, and when CCS is implemented in conjunction with biomass, the CO_2 that is re-released through combustion will be permanently stored underground. The importance of such a weapon in our arsenal against increasing CO_2 and climate change cannot be overstated. The cost of CCS technologies are of the same order of magnitude as renewable energy technologies such as wind and biomass, (about 30% more), but much less than PV. However, this estimate does not include all of the sustainability principle violations associated with coal. If these were included as part of the economic analysis, then fossil fuels with CCS would be even more expensive.

Governmental policy-makers should recognize that the complexity of the power sector requires a systems perspective and a mental framework which can be used to explore trade-offs between options. Prioritization of the strategies will be region-specific, there is no one answer to the question of which energy technology option to choose. The other key aspect is that the strategy should be as flexible and as adaptable as possible so as to incorporate changing circumstances in order to maximise society's chances of success. Initial investments in energy efficiency will provide savings which can be reinvested in a mix of renewable technologies and CCS. In order to make meaningful comparisons between technology options, sustainability violations should be quantified by including the externalities to show the overall cost to society in other sectors.

Finally, investments in fossil fuel based CCS can be a strategic step towards a sustainable stationary power sector. It should be considered a bridging technology to cope with CO_2 emissions we emit until we can successfully transition to renewable, non-polluting sources of energy. It is important to implement this technology because of the significant base of already operating coal-fired power plants, and a significant supply of coal worldwide. This transition will be greatly facilitated by sensible policy which makes CCS the least cost option when penalties such as carbon taxes or caps are in place. This is particularly important because of the possibility to "scrub" the atmosphere if biomass fuel replaces coal for power generation.

5.1 Further Research

This thesis has laid out the basic framework for analyzing energy options and consolidated the considerations that should be taken into account by policy makers to work towards meeting energy needs sustainably. This approach is generalised and cannot give an unqualified answer about the best way to achieve these goals in every situation. There are many possible paths to a sustainable energy future. Therefore, we have identified the following areas for potential further research:

- Analysis of renewable energy options in various climates and latitudes.
- Development of a predictive model for evaluating the impact of changes in demand and energy supply mix upon the CO_2 emissions of an actual energy infrastructure system. This model would be similar to

the one presented in Appendices A-C, but more comprehensive and specific to the power sector being studied. This model could include:

– Capability to perform full-cost accounting of renewable energy vs. CCS for a given supply mix/scenario.

– Analysis of the effectiveness of various policy options (e.g. taxes vs. subsidies) to achieve a given supply mix

– Consideration of peak loading (daily and seasonal variations in power demand) as well as supply variations caused by renewable power utilization fluctuations.

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Appendix A: Field Experts Consulted

Name	Position	Organisation
Dag Christensen	Director of New Energy Technologies	Norsk Hydro, Oil & Energy Division
Fredrik Hedenius	Ph.D. Candidate, studying under Christian Azar	Chalmers University
Klaus Lackner	Mineral Carbonation	Columbia University
David Bayless	Algal CO_2 Mitigation Systems	Ohio University
Martin Goldblatt	GreenFuel Technologies	MIT
Geoffrey Coates	Professor of Organic Chemistry	Cornell University

Appendix B: Computer Model Method

The model is based on the United States stationary power sector and was chosen because it is an excellent example of a large diversified power network in which fossil fuel generation is the main source of electrical supply. Based on historical data, the model generates a future Business As Usual (BAU) scenario. Power demand, mix of supply (power contribution by source), and total carbon dioxide emissions were predicted for each year between 2005 and 2104 (100 years in total). This scenario is used as a baseline for assessing our proposed strategies for strategically changing the system.

A stationary power network is inherently complex. Many simplifications and assumptions were required in order to produce a model that was manageable within the timeframe of this thesis. The major assumptions for the model are listed below:

- All power plants have equal power generating capacity, lifetime of operation, and power factors (utilization)
- The power network is an unregulated, free enterprise market in which the type of new power plant built is determined by the best financial return on investment over the lifetime of that plant
- All fossil fuel plants in the model switch over to CCS operation when and if this becomes economically viable
- Fossil fuel costs are fixed, and do not increase with resource scarcity
- All power plants operate until the end of their lifetime regardless of economic conditions

In reality, these assumptions could have a significant impact on how the system changes over time; however, we believe that the results generated by the model are qualitatively in alignment with the recommendations and conclusions presented in this thesis. A complete list of model assumptions can be found in appendix C.

A measure listed under each strategy from the C Step was incorporated as an input variable into the model. These were: power demand reduction (through energy efficiency improvements), subsidies for building new non-fossil fuel power plants, and tax on carbon dioxide emissions. These measures were not proposed as optimal or preferred choices, but were chosen specifically because they could be integrated easily into the computer model and because they represent dematerialization, substitution and abatement strategies respectively. The input variables were then adjusted independently in order to generate a scenario specific to the implementation of each strategy. Power demand, mix of supply, and total carbon dioxide emissions (both emitted and captured) were then re-calculated by the model. These results were then compared to the BAU model scenario in order to determine the relative effects of each strategy upon the model system.

A model scenario was developed to apply the three strategies in accordance with our prioritization research results. Both the magnitude and time of implementation were adjusted for each input variable. This scenario was referred to as the Strategic Sustainable Development (SSD) scenario. As with the assessment of the individual strategies, the power demand, mix of supply and total CO_2 emissions were re-calculated and compared to the BAU model scenario. This demonstrated how affective the three strategies might be when they are strategically prioritized and used in combination with one another in the context of the model system.

Appendix C: Computer Model Parameters and Assumptions

United States Power Sector Projections

Population and power supply historical data from 1950 to 2004 were used to predict the United States energy intensity (consumer electricity needs) per capita from 2005 to 2104 (EIA 2004, 228, 373). This data was also used to project the rate of deployment of renewable power in the stationary power sector over the same timeframe. Population data and projections from 2000 to 2050 were used to predict the population of the United States from 2005 to 2104 (U.S. Census Bureau, 2004). Energy intensity per capita and population were then multiplied together to project the total power demand requirements over a 100 year period.

Power Network Characteristics

The power network in the model is comprised of many individual power plants. Three types of power plants are represented in the model: fossil fuel, fossil fuel with CCS, and non-fossil fuel (renewable and nuclear). Power plants are dispatched to the power network overtime in order to meet power demand as well as to replace older plants being retired. The overall mix of supply and total carbon dioxide emissions of the power network are determined by the accumulative sum of the individual power plant contributions.

Power Plant Parameters

All three types of power plants have the following attributes:

- Lifetime of operation 30 years
- Maximum power capacity 1 GW
- Power utilization 75%

The capital cost of expenditure and CO_2 emissions produced per kWh are specific to each type of power plant. Table A.1 lists the CO_2 emitted to the atmosphere, CO_2 captured and stored, and the initial cost of electricity

(COE) for each type of power plant used in the model. For both types of fossil fuel power plants, these values were determined based on a weighted average of the amount of NGCC, PC and IGCC power supply currently used in the United States (EIA 2004, 3). The initial COE for non-fossil fuel plants was chosen such that it was greater than the average COE for renewable and nuclear technologies.

Table A.1. Power plant CO_2 emissions and initial COE[8]

Plant Type	Fossil Fuel	Fossil Fuel with CCS	Alternative Energy
Initial COE (USD/kWh)	0.045	0.070	0.090
CO_2 Emitted to Atmosphere (kg/kWh)	0.7	0.09	0
CO_2 Captured and Stored (kg/kWh)	0	0.775	0

The initial capital cost of expenditure for each power plant is calculated based on the lifetime of operation, maximum power capacity, power utilization and initial COE.

Experience Curves

Two experience curves (or 'learning by doing' curves) are used to adjust the capital cost of expenditure over the duration of a scenario. One is for fossil fuel power plants (both with and without CCS) and the other is for non-fossil fuel power plants. Based on these curves, the capital cost of expenditure for each new power plant decreases relative to the total number of power plants of that type that have been previously built.

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[8] Adapted from (Rubin 2005, 4)

Economic Assumptions:

- The power network is an unregulated, free enterprise market
- The type of new power plant built is determined by the best financial return on investment over the lifetime of that plant
- Fossil fuel costs are included in the capital cost of expenditure for fossil fuel power plants
- Fossil fuel costs are fixed, and do not increase with resource scarcity
- Economic inflation is not included
- 'learning by doing' curves are endogenous to the model, and any additional cost reductions from outside manufacturing or industry related research and development have not been considered
- The cost of energy efficiency improvements is incurred by the end user and is not represented in the model
- The non-fossil fuel subsidies are derived from sources outside of the model

Carbon Dioxide Emission Assumptions:

- All fossil fuel plants in the model switch over to CCS operation when and if this becomes economically viable
- Both new and existing fossil fuel plants are retrofit ready for CCS.
- The amount of carbon dioxide emitted and carbon dioxide stored for both types of fossil fuel plants (with and without CCS) is a fixed value.
- The capital cost of expenditure for fossil fuel plants with CCS was based on amine separation, pipeline transportation and geological storage technologies.
- Fossil fuel power plants with CCS separate 90% of the CO2 emissions from the flue gas stream.

Power Supply Assumptions:

- All power plants have equal power generating capacity, lifetime of operation, and power factors (utilization)

- All power plants operate until the end of their lifetime regardless of economic conditions
- In an over supplied energy market, power plants are prioritized in order to have the maximum affect on emission reduction. Non-fossil fuel power plants are utilized to their maximum potential first, followed by fossil fuel with CCS power plants and then fossil fuel power plants.
- Power supply and demand is constant each year (no peak loading or season variations)

Appendix D: Computer Model Results

BAU Scenario

Figure A.1 shows the BAU scenario model results for both the mix of supply and power demand for the United States power sector from 2105 to 2104. Population growth and increasing energy intensity (consumer electricity needs) are responsible for the steady rise observed in power demand. The mix of supply also changed over the duration of the model, increasing from 72 to 82 percent fossil fuel power supply.

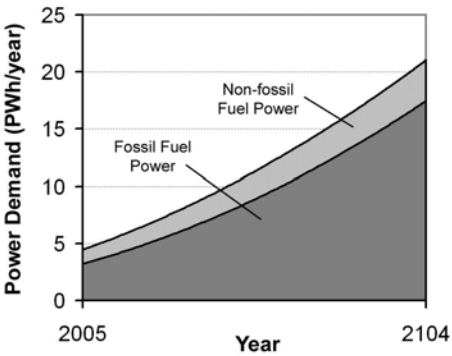


Figure A.1. BAU scenario, power demand and mix of Supply

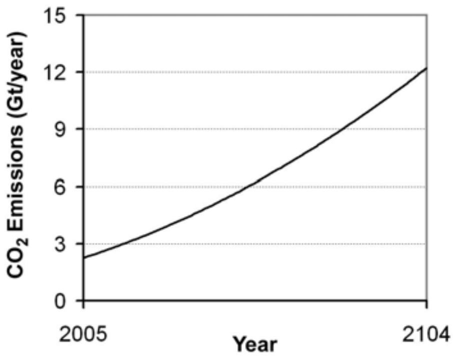


Figure A.2. BAU scenario, CO_2 emissions

Figure A.2 shows the associated carbon dioxide emissions produced by the power network. The emissions increased proportionally with fossil fuel power supply more than quadrupling over the 100 year timeframe.

To supplement our research and to understand how each strategy might affect the system, the computer model was used to illustrate the relative changes produced by each strategy in the on the model system over time.

A computer generated scenario was then developed based on our findings in order to illustrate how the system could change when all three measures are implemented strategically together.

Demand Reduction Scenario

In this scenario the dynamic response of the system caused by strengthening the Demand Reduction balancing loops was explored.

Model input variable: 25% reduction of projected power demand by 2010 and 50% by the end of 2104

Figure A.3 shows the model results for both the mix of supply and power demand from 2005 to 2104. As intended, power demand dropped significantly compared to the BAU scenario. The mix of supply was also affected, and changed in favour of non-fossil fuel power. This is primarily because the BAU rate of deployment for non-fossil fuel power plants remained unchanged. The initial drastic reduction in power demand created a temporary surplus of power supply in the power network. In this situation, non-fossil fuel power is completely utilized before fossil fuel power. This contributed to the favouring of non-fossil fuel power in the mix of supply. Figure A.4 shows the carbon dioxide emission results. By the end of 2104, the emissions were 60% less than the BAU scenario. This was 10% greater than the amount of demand reduction, the difference of which was produced by the change in mix of supply.

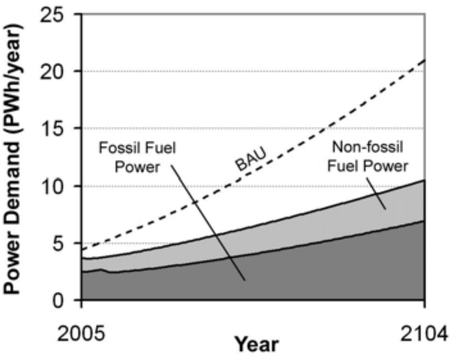


Figure A.3. Demand reduction scenario, power demand and mix of supply

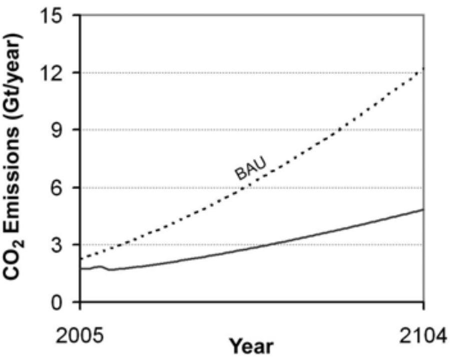
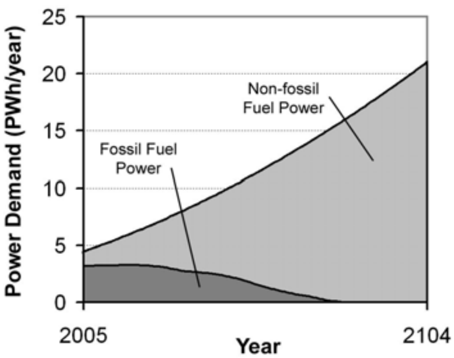


Figure A.4. Demand reduction scenario, CO_2 emissions

Non-fossil Fuel Power Scenario

For simplicity, the model combines renewable power and nuclear power together into non-fossil fuel power and makes non distinction between which type of technology is developed. In this context, the dynamic response of the system caused by increasing non-fossil fuel power is equivalent to strengthening the Renewable Power balancing loops.

Model input variable: 150 billion USD non-fossil fuel power capital expenditure subsidies available per year with a 1% growth rate commencing in 2005



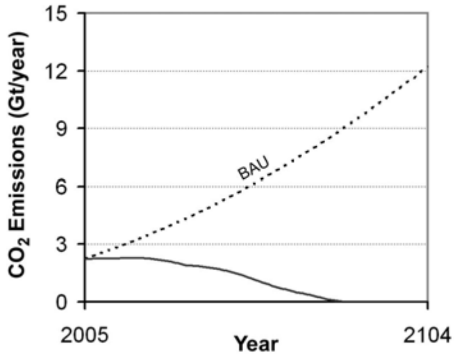


Figure A.5. Non-fossil fuel scenario, power demand and mix of supply

Figure A.6. Non-fossil fuel scenario, CO_2 emissions

Figure A.5 shows the model results for both the mix of supply and power demand from 2005 to 2104. In this scenario, the power demand was unaffected by the input variable and follows the BAU scenario. The mix of supply gradually transitioned towards complete non-fossil fuel power, as capital cost reductions from both subsidies and development of non-fossil fuel technologies (experience curves) prevented fossil fuel power from being economically competitive. By the end of the scenario the capital cost of expenditure for non-fossil fuel power plants had become less than that of fossil fuel power plants. Subsidies were therefore no longer required to make non-fossil power plants cost effective. Figure A.6 shows the carbon dioxide emissions compared to the BAU scenario. They immediately level-off and transition to zero in accordance with the phasing out of fossil fuel power plants.

Carbon Capture and Storage Scenario

In this scenario the dynamic response of the system caused by strengthening the Carbon Capture and Storage balancing and reinforcing loops was explored. The amount of carbon tax was intentionally set so that fossil fuel plants with CCS would remain economically viable throughout the duration of the scenario.

Model input variable: 40 USD/tCO2 carbon tax commencing in 2005

Figure A.7 shows the model results for both the mix of supply and power demand from 2005 to 2104. Both the power demand and non-fossil fuel contribution to mix of supply was unaffected by the input variable. The fossil fuel mix of supply changed quite rapidly over to CCS as plants implemented this technology to reduce their operating costs. Figure A.8 shows both the carbon dioxide emissions emitted to the atmosphere and captured and stored. The emissions were reduced considerably compared to the BAU scenario, but still continue to increase at rate proportional to the increasing fossil fuel power supply. The carbon dioxide captured and stored is shown to exceed the emissions generated in the BAU scenario. As described previously, this is because fossil fuel plants with CCS operate less efficiently and require greater amounts of fossil fuel to produce the same amount of electrical power.

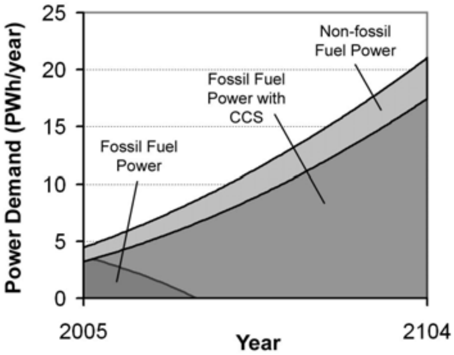


Figure A.7. CCS scenario, power demand and mix of supply

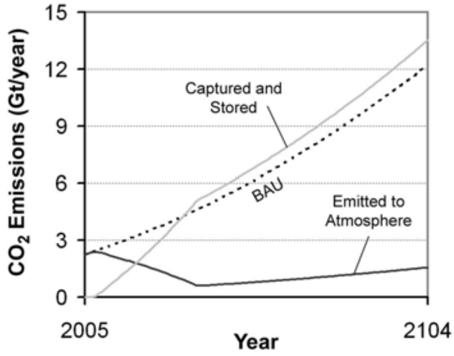


Figure A.8. CCS scenario, CO_2 emissions

Strategic Sustainable Scenario

In this scenario the dynamic response of the system caused by strategically implementing all three strategies together was explored. The magnitude and time of implementation of the input variables were adjusted in conjunction with one another. This was done in a manner that produced a scenario that minimized both the carbon dioxide emissions and magnitude of each input variable. This scenario is referred to as the Strategic Sustainable Development (SSD) scenario.

Model input variables: 15% reduction of projected power demand by 2010 and 30% by the end of 2104, 25 billion USD non-fossil fuel power development subsidies available per year with a 1% growth rate commencing in 2005, 30 USD/tCO2 carbon tax commencing in 2010

Figure A.9 shows the model results for both the mix of supply and power demand from 2005 to 2104. As expected, power demand drops noticeably compared to the BAU scenario. The mix of supply distinctly changed twice over the 100 year timeframe. The first major change occurred when all of the fossil fuel power plants switched over to CCS. This was caused by the carbon tax on emissions. The second major change occurred when all of the fossil fuel power plants with CCS were replaced by non-fossil fuel power plants. Capital cost reductions from subsidies and development of non-fossil fuel power plants was responsible for this change. Figure A.10 shows the carbon dioxide emissions associated with this scenario. The emissions were reduced dramatically compared to the BAU scenario and rapidly approach zero in the first half of the 100 year timeframe. The amount of carbon dioxide captured and stored is relatively little compared with the BAU emissions and also approaches zero in accordance with the phasing out of fossil-fuel power generation.

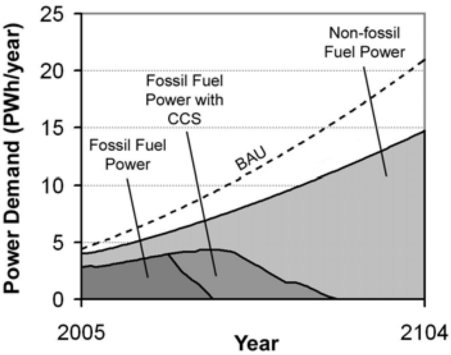


Figure A.9. SSD scenario, power demand and mix of supply

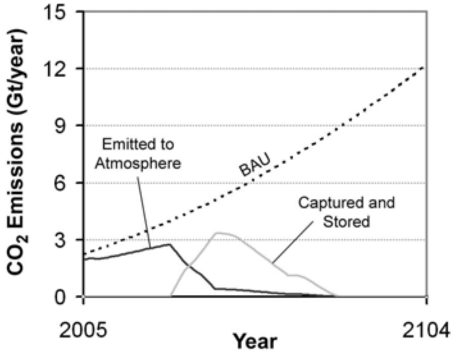


Figure A.10. SSD scenario, CO_2 emissions

Appendix E: Author Contributions

This thesis is a collaborative work of Lisa Chacón, Benjamin Hornblow, Daniel Johnson, and Christopher Walker as a requirement for Masters' degrees in Strategic Leadership towards Sustainability in the Spring of 2006.

All group members contributed equally to the research, synthesis, report writing, the shared mental model of the System represented by the CLD and presentations.

Lisa was responsible for research on coal, natural gas and biomass. She wrote the abstract, executive summary, and significant portions of the introduction, discussion and conclusion sections.

Benjamin was responsible for research on geothermal, nuclear and CO_2 separation technologies. He wrote significant portions of the Method and Results step A and step C1 sections. He created the computer model, analyzed the results, and wrote Appendices B, C and D. He also drafted the first CLD which was further developed by all members of the group.

Chris researched wind and ocean power, demand reduction, renewable power analysis and policy options, as well as ocean carbon storage. He wrote significant portions of the discussion section.

Daniel researched photovoltaic and hydroelectric power and geologic carbon storage options. He was responsible for compiling and editing the results and references sections, organizing group documents and maintaining consistency in the final thesis.