# PLANNING RENEWABLE ELECTRICITY USING LIFE-CYCLE ANALYSIS

by

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# ABSTRACT

It has been predicted that by the mid-21st century worldwide energy demand will grow two to three times the current level of demand. Expanding the global electric power generation capacity will be problematic using the three predominant methods, namely, nuclear fission, fossil fuels and hydropower. There are few suitable sites left for new large-scale hydropower dams. Both fossil fuels and nuclear fission have widespread environmental consequences to their use and the supply of fuel for these two technologies is a non-renewable resource. Renewable energy system (RES) technologies have been proposed as the means to expanding energy markets in a sustainable manner.

A formative step in deploying RES will be the design of a standardized methodology for determining policy and planning decisions to initiate market and government support for these nascent technologies. This thesis outlines the design of a RES planning model based on the life-cycle analysis (LCA) methodology. The proposed model will integrate a climatologically-based renewable energy optimization and simulation (REOS) model into the LCA. Goal-attainment algorithms will be used to find feasible installed capacities for power generation which will meet a prescribed load demand and simultaneously attempt to meet desired policy targets. The policy targets here will be the per-kilowatt hour price of power, life-cycle air-borne $CO_2$ emissions, and the land requirements of the system. An analysis of the performance of RES technologies in two Canadian cities that already have mature electricity utilities is done to demonstrate the methodology.

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# CHAPTER 1: INTRODUCTION

## 1.0 BACKGROUND

Currently, the world's electricity is generated from about 70% fossil fuels, 15% nuclear energy and 15% hydropower [Brown, 1996]. Approximately one-fifth of the world's population uses over 75% of this electricity. Overall energy production and consumption worldwide (which includes transportation, agriculture, and non-electric cooking and heating) is around 88% fossil fuels, 8% nuclear and 4% hydro power [Berrie, 1992]. Due to capital shortages, growing populations, political instability and natural resource limitations, four-fifths of the world have not experienced the levels of industrialization that characterize the developed world (notably, but not exclusively; U.S., Western Europe and Japan). Driving much of the developed world's industrialization has been the historically recent (80 years) explosive growth in energy use by these nations. As an example, since 1700 the U.K. has increased its per capita energy use by almost 15 times (400 to 5400 kg coal equivalent per capita). As a measure of development, per capita energy use is a fairly indicative value. For instance, per capita energy use in 1997 was 11209 kg coal equivalent in Canada (developed), 3772 kg coal equivalent in South Korea (developing), and 332 kg coal equivalent in Pakistan (less developed) [Economist, 1998]. Unlike the developing world, which is now undergoing rapid and sustained energy expansion of 4% per year, the developed nations are reaching a plateau to their energy consumption (increasing approximately 0% to 1% per year) [Flanagan, 1993]. These predictions in energy consumption are seen as long-term trends that should last well into the next century. One of the global challenges in the coming years will be to meet the world's increased demands for energy.

The worldwide response to this challenge has been twofold; namely conservation efforts and increased energy generation. By adopting more energy efficient appliances and lifestyle practices, industrialized countries have been able to greatly curtail increases in their per capita energy use [Berrie, 1992]. As has been noted though, that even with approximately two decades of conservation efforts (since the oil crisis), the industrialized world's energy consumption still accounts for more than 60% of the world's total consumption, whereas it accounts for less than 20% of the world population. The developing countries have been undergoing an unprecedented expansion in both their economies and industrial bases. Industrialization around the world has put a heavy reliance on the most plentiful and available large-scale energy source; namely fossil-fuels. The global response to increased energy demand has been mostly fiscally-motivated, but as environmental tolerance within cities and regions is exceeded, other motivations such as social equity and environmental responsibility will also become (and in some places already are) issues in energy-related decisions.

The world is facing large environmental hazards as the global natural resource base becomes depleted and polluted. Air, water, and soil are all despoiled by much of the industrial and power generation activity that is ongoing today. Nuclear energy, oil- and coal-fired power plants, and deforestation/defoliation for firewood, all heavily contribute to the worldwide deterioration of the shared global environment. The recognition of international environmental problems has spurred on multilateral efforts to help find solutions to these problems [Rio, 1992], [Kyoto, 1997]. It has been projected that world energy demand without conservation efforts will double within the next 20 years [Wrixon, 1993], and even with aggressive energy conservation policies it should double within the next 40 years [Johansson, 1993]. Thus, one may conclude that whether managed or not, the world energy production market will see very large future growth. As energy markets open and change with available technologies, there is a possible future in which the predicted deleterious effects of future industrial growth may be lessened to more manageable levels through a more sustainable and ecologically-focused energy generation model.

In traditional power planning, the technologies that were available consisted predominantly of fossil-fuels, hydropower, and nuclear energy. These technologies' power characteristics are controllable and predictable given the assumption that the generators would be provided sufficient fuel [Stoll, 1989], [Berrie, 1983]. The goal of the planner was essentially to find the optimal dispatch of network power generators in order to satisfy the usually conflicting goals of service reliability and monetary costs (this is commonly known as least-cost planning). Today, this traditional power planing model has also had to introduce contemporary issues dealing with the environment and social equity. Because of the known profound effects that power projects can have on its locale, today's power project plans must usually undergo the scrutiny of environmental and social analysts, as well as meeting standards for economic and technologic feasibility.

Integrated renewable energy system (IRES) power networks introduce new constraints and uncertainty into the traditional planning methods. Wind and solar-based renewable technologies rely on the continuous availability of wind and sunshine to generate power. Prediction of climatic conditions is a problematic endeavour and thus, in assessing the performance of IRES power networks, the problems in predicting weather conditions introduces uncontrollable and unpredictable power output into the planning process. In addition, spatial constraints must also be addressed because of the far-flung and distributed nature of IRES installations.

This study is concerned with the high-level design stage where the planner's goal is to determine reasonable estimation of the overall facility deployment for servicing a projected load demand. Power network simulation and goal-programming are used to analyze and design against engineering, economic and environmental targets. Life-cycle analysis (LCA) is used to demonstrate how environmental considerations are introduced into the high-level planning exercise. Overall, this study presents a methodology for planning of IRES power networks in which environmental criteria may be addressed in the design by integrating a power simulation/goal-programming system into a life-cycle analysis (LCA) framework.

## 1.1 SYSTEM COMPONENTS

The methodology presented in this report is based on the life-cycle analysis methodology (LCA) [Vigon, 1993], [Curran, 1996], [Ciambrone, 1997]. Life-cycle analysis (LCA) is a methodology through which environmental problems related to human consumption can be evaluated. It is a comparative approach in which alternative products and processes are assessed to find their relative fitness and performance. The LCA methodology consists of 5 stages; namely (and in order of execution), goal determination, system scope, inventory audit, impact assessment and system improvement. The presented methodology shows how a power planning model and goal-programming design system are incorporated into the five-stage LCA study.

The power planning model is based on the renewable power simulation presented in [Venema & Ali, 1998]. The simulation assumes a single-point centralized load with a grid-connected IRES network. The overall simulation is used as a sub-component for a goal-programming software system. The goal-programming component is based on the capabilities and specific requirements of the Matlab 5.0 mathematical software system's goal-attainment algorithms (*attgoal*) [Matlab, 1998].

Feasibility studies for deploying IRES technologies are conducted for two Canadian sites; London, Ontario and Whitehorse, Yukon. The climatic simulation is conducted using 5 years (1989-1993) of weather data from the Canadian Weather for Energy Calculations database [CWEC,1997].

## 1.2 OUTLINE OF THE THESIS

This research thesis outlines the methodological issues in integrating IRES power planning into the life-cycle analysis framework. In particular, the thesis focuses on analyzing the planning of new IRES installed capacity within an established and mature electricity grid.

The major contribution of this research is to demonstrate the efficacy and applicability of the life-cycle analysis methodology as a complementary method to standard energy planning in order to address environmental criteria in the planning stages of a power development project. In addition, a simplified implementation of an IRES planning system based on existing literature will be demonstrated.

The report structure presents the background and literature reviews for power planning (ch. 2) and life-cycle analysis (ch. 3). Special sections are included in both of these chapters to address and highlight relevant issues in RES technologies. The LCA exercise begins with the goal determination stage (where the products and limitations of the study are defined) and continues with the setting of the system scope and boundaries (ch. 4). The life-cycle inventory for the various material components of the IRES system is then conducted by quantifying component materials' emissions, energy and land requirements (ch. 4). Chapter 5 presents the power simulation and goal-programming results for London and Whitehorse for designing networks using the three design variables of land requirements, price of power and $CO_2$ emissions. Chapter 6 concludes the overall study with conclusions and recommendations.

# CHAPTER 2: A REVIEW OF RES TECHNOLOGIES AND POWER PLANNING

## 2.0 INTRODUCTION

The following sections outline the technologies and some of the assumptions that are used for modelling an integrated-renewable energy system (IRES) network. Section 2.1 provides an overview of current trends in renewable energy technologies. Section 2.2 uses a power balance equation to demonstrate one method for conducting a least-cost planning exercise with standard electric generation technologies like coal or nuclear power. Section 2.3 shows the differences that occur from applying the power balance of Section 2.2 to IRES technologies.

## 2.1 RENEWABLE ENERGY SYSTEM TECHNOLOGIES

Renewable electricity generation entails a number of different conversion technologies. These technologies convert into electricity some of the energy that is contained in continuous natural events, such as ocean tides, sunshine, geothermal geysers, winds, and carbon-based fuel from biological materials. In recent years, the technologies of solar photovoltaics, wind turbines, and biomass fuel conversion have progressed to the point that they may be soon competitive in their prices with other more familiar energy technologies such as fossil fuels and nuclear energy. The following sections briefly outline some of the ideas and current trends that are prevalent in commercial systems of these three technologies.

### 2.1.1 WIND TURBINE GENERATORS

Commercial wind turbine generators (WTG) are usually classified into three main groups. The peak power output of the single WTG plant defines its class. The table below outlines the details of WTG classifications.

| *Class* | *Plant Size* | *Uses* |
|---|---|---|
| Small | <10 $kW_p$ | Water pumping, agriculture |
| Intermediate | 10 – 150 $kW_p$ | Remote stand-alone applications |
| Medium-to-large | 200 – 800 $kW_p$ | Grid-connected WTG |

*Table 1: Wind turbine applications and the approximate power requirements*

Experimental machines range in sizes (as measured in peak power) from hundreds of $kW_p$ to up to 4 $MW_p$. But for commercial applications, these very large machines have proved to be cost prohibitive because of their enormous size. Johannson (1993) explains this with a simplified heuristic that the energy captured by a rotor increases with the square of the radius, whereas the mass, and thereby the cost, will increase with the cube of the rotor diameter. With current materials, the optimal size of WTG for a first class wind resource has been found to be 200 to 500 $kW_p$.

There are two main types of WTGs that are used; vertical-axis wind turbines (VAWT) and horizontal-axis wind turbines (HAWT). Figure 1 below depicts the major differences between the designs of the VAWT and the HAWT windmills. In the U.S., the DOE and various utilities have aggressively pursued research and operation of the VAWT design (whereas most research outside of the U.S. has concentrated on developing HAWT technologies). VAWT, or the Darrieus turbine, offers advantages over the HAWT in that the yaw system for the windmill is simpler, the rotors use light-weight airfoils held together by tension wires and the maintenance of the facility is made simpler because the controls and turbine are all at ground level. In addition, the performance and efficiency of the VAWT are comparable to that of the HAWT. One of the main reasons that some researchers doubt its wide-scale use outside of the U.S. is that the VAWT is not easily able to utilize winds at higher heights (over 40m). Unlike the HAWT, which easily accommodates higher towers.

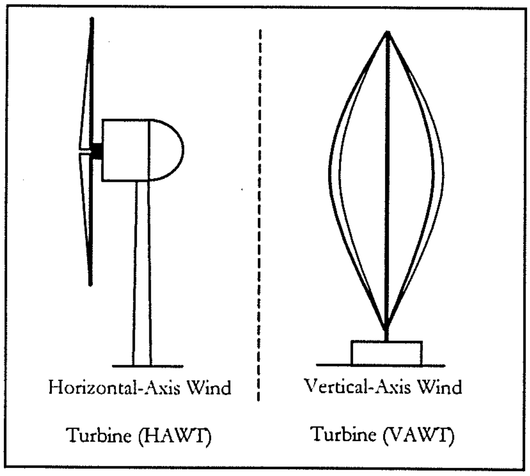

*Figure 1: Illustrations of the horizontal-axis and vertical-axis wind turbines*

WTG's are the most mature of the renewable energy technologies considered in this review. Worldwide there is approximately 3700 $MW_p$ of installed wind capacity. The bulk of these installations are in California and throughout Europe. According to EUREC (1996) the growth of the global wind industry has been very rapid in the 1990's. The table below shows estimates of the worldwide installed wind capacity in the years of 1993 to 1995.

| **Year** | **Installed** |
|---|---|
| 1993 | 541 $MW_p$ |
| 1994 | 642 $MW_p$ |
| 1995 | 1200 $MW_p$ |

*Table 2: Estimated worldwide WTG installations for 1993-95*

The World Energy Commission (WEC), projected that at current growth rates wind energy will be at least 180 000 $MW_p$ by the year 2020 [WEC, 1993]. With a more "eco-driven" policy, they predict that the installed wind capacity could be as high as 474 000 $MW_p$, or 5% of the total projected global energy demand in the year 2020.

These future estimates are based upon the high performance that field tests have yielded around the world. Today, wind-derived electricity is at cost parity to both fossil-fuels and nuclear energy when external and social costs are added to the direct costs of generation. The International Atomic Energy Association (IAEA) predicts that by some time between the years 2005 to 2010, wind energy will have a lower overall cost than traditional non-renewable energy and will be at near par even when only current direct costs are considered [IAEA, 1993]. As per the performance of the current WTG's, the availability and system efficiencies are achieving near their theoretical limits. For instance, the Dutch experience has measured an availability of power which is between 98-99% [DWTMA, 1998]. With newer tools, such as remote sensing for siting and more reliable components for turbines, power output estimates are usually within a margin of 15% of the actual power output. The maximum theoretical efficiency of WTG is 50% [Wrixon, 1993]. Current plants have reported efficiencies of up to 45% during periods of optimal wind conditions. The year-round average performance of the Dutch and California wind farms had efficiencies between 15 to 22% [DWTMA, 1998], [Walker, 1997].

Areas where there is still a lot of research activity include finding new materials for rotors and turbine components, designing variable speed rotors, and more robust stall controlled airfoils for higher hub heights. Johansson(1993) predicts that these activities could potentially produce systems that produce 10% more power than current systems.

### 2.1.2 SOLAR PHOTOVOLTAICS

Solar photovoltaics is the conversion of sunlight into electricity via the use of photoelectric materials. There are two major types of solar photovoltaic systems. The first and only commercial system is flat-plate photovoltaics which consists of simply a flat surface such as ceramics or glass which has been coated with a photoelectric substrate. This system converts both direct and diffuse light into electricity. The other system that is still in an experimental stage is the concentrator module. Concentrator modules use mirrors and lenses to focus direct sunlight onto a flat-plate. Concentrators achieve higher efficiencies but problems in tracking the sun and the mechanical durability of the system has made it problematic in actual implementations. The following sections will deal solely with flat-plate technologies.

According to EUREC (1996), solar photovoltaic systems are currently being installed at a rate of about 80 $MW_p$ per year with a projected annual growth of about 15% in new installations per year. These installations are mostly remote applications in agriculture, telecommunications, and rural development projects. The payback periods for these systems is approximately 2 to 6 years in regions of high to medium intensity sunlight (often referred to respectively as sunbelt and continental regions).

At present there are a number of different designs in flat-plate systems. All of these flat-plate technologies utilize production methods that are akin to semi-conductor fabrication. As with microchip manufacture, this means that the size and weight of the substrate highly affects the cost and environmental performance of production. These designs are broadly defined as silicon, thin-plate (also referred to as thin-film) and multi-junction cells. Silicon cells are the most widely used design (approximately 80% installed capacity of the world market is silicon-type solar cells). These cells are characterized as being made of either mono-crystalline or poly-crystalline silicon substrates. These substrates are relatively thick and are relatively costly to manufacture. Current silicon photovoltaic systems generate electricity at around US$0.35-0.65/kWh, whereas commercial viability is around $0.10/kWh. As a result, researchers have designed thin-plate designs in which the substrate is significantly thinner (on the order of 10 times) and thus the cost of forming the substrate is greatly reduced. The trade-off for these thin-plate designs is that they use chemicals such as cadmium, tellurium, indium and a number of other heavy metals, which are potentially very hazardous materials. Thin-plate technologies achieve approximately the same, if not higher, efficiencies and use a more reliable manufacturing process. Another type of thin-plate cell is the amorphous silicon cell that uses a thin silicon substrate. Its manufacture is very low cost on a per unit area basis, but unlike mono- and poly-crystalline silicon cells which achieve around 10% efficiency, amorphous silicon achieves roughly 5% efficiencies [Markvaart, 1993]. The following table outlines the performance of the various cell types both in lab conditions and as commercially available cells.

| **Cell Type** | **Lab Efficiency** | **Commercial Efficiency** |
|---|---|---|
| Mono-crystalline silicon | 23% | 10-12% |
| Poly-crystalline silicon | 18% | 8-9% |
| Amorphous silicon (a-Si) | 13% | 3-5% |
| Gallium Arsenide (GaAr) | 25.5% | n/a |
| Copper indium selenide (CIS) | 15% | n/a |
| Cadmium Telluride (CdTe) | 15% | n/a |

*Table 3: State of photovoltaic cell technologies*

Current research is heavily involved in two main areas; the first being the improvement of manufacturing techniques for thin-film cells and the second being the development of multi-junction cells. Multi-junction cells capture more than one band of the light spectrum within the same cell area. Thus, theoretically more of the light energy can be captured on a per unit area basis. These research efforts combined with mass production methods should be able to bring the price of solar photovoltaics down significantly from its current relatively high per kWh cost [Johansson, 1993], [EUREC, 1996]. The table below summarizes some of the projected performance advances in solar photovoltaic systems.

| **Item** | **Short-term (by year 2000)** | **Medium-term (by year 2010)** |
|---|---|---|
| Crystalline Silicon | 16-18% | >20% |
| *Amorphous Silicon* | >10% | *>15%* |
| Thin-Film Advanced | *>20%* | 25% |
| Module Lifetimes | 20 yrs | 30 yrs |
| Inverter efficiency (AC power conditioning) | 90-97% | 95-98% |
| Consumer cost of power (per kWh) | $0.15-0.20 | $0.05-0.10 |

*Table 4: Estimated performance of various PV technologies*

### 2.1.3 BIOMASS CONVERSION SYSTEMS

A biomass conversion system uses biological material as feedstock for power generation. According to EUREC (1996), it is the fourth largest energy source worldwide. This translates to 14% of global primary energy demand. In developing countries, biomass-derived energy accounts for up to 35% of primary energy demand. One of the reasons that biomass has been so widely used is that it is available almost anywhere habitable by man, and there are numerous methods for extracting energy from biomass.

The feedstock may be burned and the heat energy is used for cooking or to drive a steam turbine. Other methods of biomass energy extraction are to produce intermediate fuels such as ethanol, or bio-gas through chemical processes such as anaerobic digestion, distillation or liquefaction. The feedstock also may be of any number of different species of plants or animals. But, biomass feedstock is usually classified under four major groups:

(i) Municipal solid waste (MSW)

(ii) Agricultural and lumber residues and waste

(iii) Wood energy

(iv) Energy cropping of short rotation forestry, or herbaceous lignocellulic (stalky) grains and cereals

Municipal solid waste (MSW) refers to material that is combustible and is usually landfilled. One of the problems of the latter half of the twentieth century was to find space for the refuse generated by cities. One scheme that seemed to make sense was to incinerate the refuse, thus making it much more compact, but at the same time use the heat to run steam turbines. The major problem with this system was that any harmful chemicals in the waste were passed into the atmosphere and local water sources. Although, MSW is still practiced, it is not a widely used fuelstock because of the negative environmental effects.

Combustion of agricultural and lumber wastes is probably the most popular method currently for producing electricity from biomass. This is because the materials are usually free of large amounts of unwanted pollutants, and the cost is very low because it is unused waste material. These materials are often used in small generators (< 1 MW) which also produce centralized heat for small settlements (often termed co-generation). Commercial and industrial wastes are used but these are considered much like MSW because of the chemical pollutants that are typical of large industrial processes.

Agricultural waste materials are also used in both anaerobic digestion systems, which produce bio-gas for cooking (dung, crop residues) [Ravindranath, 1995], or distillation processes that produce alcohol-based fuels for use in vehicles or power plants (e.g. bagasse from sugar cane) [Tillman, 1991]. Lumber waste is usually used as feedstock in order to run remote steam co-generators. But, lumber, in general, has a larger monetary value as a commodity for the furniture, construction, or paper industries.

As far as research and development, much interest has been generated from ideas in energy cropping. The two most dominant forms of energy crops that are being considered are herbaceous lignocellulic biomass (e.g. perennial grasses and cereals), and short rotation forestry (e.g. willows, poplars). There are a number of motivations behind the development of energy cropping. One of the motivations is the trend of industrialized nations to subsidize their agricultural industries to restrict the amount of commercial crops harvested each year to keep prices stable. Another motivation is the desire of governments around the world wanting to conduct costly environmental remediation on polluted areas. Finally, global-warming is seen as a problem which stems mainly from air-borne carbon emissions from fossil-fuel combustion, thus there has been a great deal of debate as to how to curtail and control these emissions. Numerous authors have espoused the use of biomass cropping as a possible solution to these trends and problems [Cook, 1996], [Mann, 1996], [Wright, 1993], [Coiante, 1996], [Ledin, 1996a].

Traditional methods for extracting energy from biomass has been direct combustion, pyrolisis to produce charcoal, fermentation and distillation of alcohol, and anaerobic digestion to produce bio-gas. More modern methods that have emerged in the last three decades are the thermochemical conversion processes of gasification and liquefaction. These methods produce relatively high-energy content fuels of methanol and heavy oil, respectively. These fuels can then used within large electric power plants (30+ $MW_p$). These fuels are clean burning and easily transportable. The most popular commercial system is called the biomass integrated gasification gas turbine (BIG/GT). The gas turbine uses jet engine technology (as opposed to steam turbines) to produce electricity. Even as the steam engine has begun to reach its theoretical maximum thermodynamic efficiency, jet engines have been undergoing development and progress in power output and overall system efficiencies. Currently in the U.S., 9000 MW of biomass derived power has been installed to date. U.S. and European companies are currently developing BIG/GT systems that are capable of generating 250MW of power.

By harvesting fast growing indigenous plant species, which are often pest-resistant and do not require large amounts of fertilizer or herbicide inputs, researchers have investigated some of the environmental and economic effects. From Mann (1996), the indications are that 95% carbon-closure, which is the amount of carbon released to the atmosphere from the system divided by the carbon that the system sequesters, could be expected from biomass generation. Future retired agricultural land that has been set aside for no planting is estimated to be in the millions of hectares in both Europe and North America. EUREC (1996) predicted that by the year 2000 there would be 20 million hectares of retired agricultural land in the EC12, and 10-20 million more hectares of marginal industrial land.

Biomass conversion systems still need a lot of research and development for finding or breeding pest-resistant species of plants for the many different regions of the world where this technology could prove fruitful. Dedicated biomass cropping has many benefits in that a new energy economy may be emerging which will help to ease the economic crunch on the industrialized countries' rural communities. However, wide-scale biomass systems have the potential to do great harm to the environment. Intensive agriculture could spur soil erosion and local ecosystem disruptions. The processing of biomass in thermochemical processes produces liquid and solid wastes in the slurry after the fuel extraction has been completed. The performance of these systems is very much a function of the local biota and the management techniques employed.

## 2.2 POWER PLANNING

### 2.2.1 GENERAL PROBLEM

Power network planning has been based around the two main goals of adequately servicing a load demand and achieving a desired life-cycle economic performance from the network. The difficulty in introducing renewable technologies into standard power planning methods is that climate-based constraints are pervasive and inherent to most measures of the IRES network's performance, cost and feasibility.

The basic problem outlined in the following sections is that the planning model used for IRES compared with standard planning methods for conventional power generation (nuclear, fossil fuel and hydropower) must be augmented with the LCA in order to account for added environmental constraints.

The planning method for conventional power systems usually involves the following two iterative steps:

(i) Assessing how well a chosen power regime will satisfy some foreseen power demand

(ii) Iterations over step (i) in which changes to the power regime are evaluated until desired goals in cost and quality are achieved.

As will be demonstrated, these two basic steps remain the same, but the overall system of equations and decisions in the planning process for IRES changes. Utility planning is concerned primarily with finding the three inter-related quantities of:

a. Forecast load demand

b. Size and regime of the installed capacity of generators

c. Unit price of electricity to consumers in relation to reliability or quality of service measures

This thesis examines only (b) and (c). Concern (a) was considered beyond the scope of this work.

## 2.2.2 STANDARD METHOD FOR DETERMINING THE POWER SYSTEM INSTALLED CAPACITIES

The most basic equation used in power planning is the simulation of load demand and power generation. This is often termed as the load balance equation. For a single load with multiple generators over hourly timesteps, the load balance can be simply expressed as:

$$U[t] = \max(L[t] - \sum_{i=1}^{k} P_i[t], \quad 0) \qquad (2.1a)$$

$U[t]$ ≡ unserved load demand at timestep $t$ (kWh)
$L[t]$ ≡ load demand at timestep $t$ (kWh)
$k$ ≡ total number of power sources
$P_i[t]$ ≡ power output from generator $i$ at timestep $t$ (kWh)

The power output from the generators must also adhere to the physical constraints of the generators. The maximum power output and dispatch characteristics of the power source must be met. In a system where there is simply a limit to the upper power output of a plant, the power constraint would be an expression of the restrictions on the loading of the generator. This may be expressed as:

$$\frac{P_i[t]}{P_{\max,i}} < lf_{\max,i} \qquad (2.1b)$$

$P_{max;i}$ ≡ maximum rated power output for generator $i$
$lf_{max;i}$ ≡ maximum load factor for generator i

The load balance (Equation 2.1a) is then subjected to a general cost target function, which in equation (2.2) calculates a per kWh cost, based on the total cost of the network.

$$C = \frac{\sum_{i=1}^{k} c_i}{\sum_{t=0}^{T} (L[t] - U[t])} \qquad (2.2)$$

$T$ ≡ number of timesteps in simulation
$c_i$ ≡ cost of generator $i$ over time period $T$ ($)
$k$ ≡ total number of power sources
$C$ ≡ cost per unit power for network

One of the other main factors in power planning is the reliability and quality of the network to meeting load. This step attempts to correct for problems such as blackout and "brownout" conditions. These problems occur because of either insufficient capacity in the network, fuel shortages or ill-planned dispatch of power from the generators. Two of the most widely used reliability measures are loss-of-load-probability (LOLP) which is a measure of the system's inability to meet the daily maximum load, and loss-of-energy-expectation (LOEE) which measures how much load is expected to be unserved over a particular period [Berrie, 1983]. In this study, a simplified measure was used which has been termed the percentage unserved load. It is simply a constraint on the percentage of load demand that went unserviced through the period of simulation.

$$\frac{\sum_{t=0}^{T} U[t]}{\sum_{t=0}^{T} L[t]} \leq ue \qquad (2.3)$$

$ue$ ≡ maximum allowable unserved load percentage

So, in order to find the dispatch for the optimal cost, $C$ from equation (2.2) is minimized subject to the constraints of equations (2.1a), (2.1b) and (2.3):

$$\min C \quad s.t. \quad (2.1a),(2.1b),(2.3) \quad are \quad satisfied \qquad (2.4)$$

## 2.3 DEALING WITH RENEWABLE TECHNOLOGIES IN DETERMINING INSTALLED CAPACITIES

Integrated renewable energy systems (IRES) use the same basic set of equations and constraints as standard power systems for power planning. All of the equations (2.1a), (2.1b) and (2.2)-(2.4) still apply to the renewable's scenario. But, IRES technologies add another physical dimension to the power planning methodology because of their constraints on power production from spatial and climatic issues. The problems are three-fold:

1. Renewable technologies are not subject to a controllable loading of the generator and must have their power dispatched, off-loaded or both depending on whether the load has been surpassed.
2. Maximum power at any time period is due to stochastic climatic variations such as wind speed or solar irradiation rates
3. Siting plays a significant role in the maximization of power conversion from IRES technologies.

The following additions to equations (2.1-2.4) will deal with the first two of the aforesaid problems. The third problem, which deals with the effects of siting on IRES power output, was beyond the scope of this report.

For solar photovoltaics and wind turbines, the overall area of coverage governs the magnitude of power output. This is explained in more detail in Chapter 4. The area of coverage for these technologies is proportional to their installed capacities. For this discussion, the area of coverage is introduced into the planning model as new constraints on the power output of a generator. Additionally, the constraint includes a new variable which is referred to as a power density. It is simply a measure of the per unit area resource available to a particular technology for energy conversion. Thus, the power density multiplied by the area of coverage equals the maximum power output in a particular time period.

$$P_i[t] \leq p_i[t] \cdot a_i \qquad (2.1c)$$

$p_i[t]$ ≡ per unit area power density for generator $i$
$a_i$ ≡ area of coverage for generator $i$

Unlike solar photovoltaics and wind turbines, biomass conversion systems are the same as other fossil-fueled technologies. However, for an ideal regionally sustainable system, biomass conversion would be based upon only the fuelstock that was grown and distilled locally. This would add a second IRES constraint in the storage and growth potential for a region. Simply, this constraint would recognize that the fuel used between two subsequent harvests would need to be less than or equal to the storage at the time of the initial harvest plus the fuel produced from that initial harvest. This could be expressed as,

$$S_{j+1} = S_j + H_j - F_{j+1}, \quad S_j \geq 0, \quad (2.1d)$$

$S_j$ ≡ Stored fuel in period $j$
$H_j$ ≡ Harvested fuel in period $j$
$F_{j+1}$ ≡ Fuel consumed in period $j+1$
$j$ ≡ Harvest period

So, in order to find the dispatch for the optimal cost in the IRES, equation (2.2) is minimized subject to the constraints of equation (2.1a-d) and (2.3):

$$\min C \quad s.t. \quad (2.1a),(2.1b),(2.1c),(2.1d),(2.3) \quad are \quad satisfied \qquad (2.5)$$

## 2.4 SUMMARY OF PLANNING METHODOLOGIES

The two methodologies of standard power planning and planning with IRES are shown below in figures 2 and 3, respectively. In general, they are both based on the same power balance equation but the climatic constraints imposed by immediate dispatch renewable technologies increases the complexity of the IRES network at this particular level of network simulation.

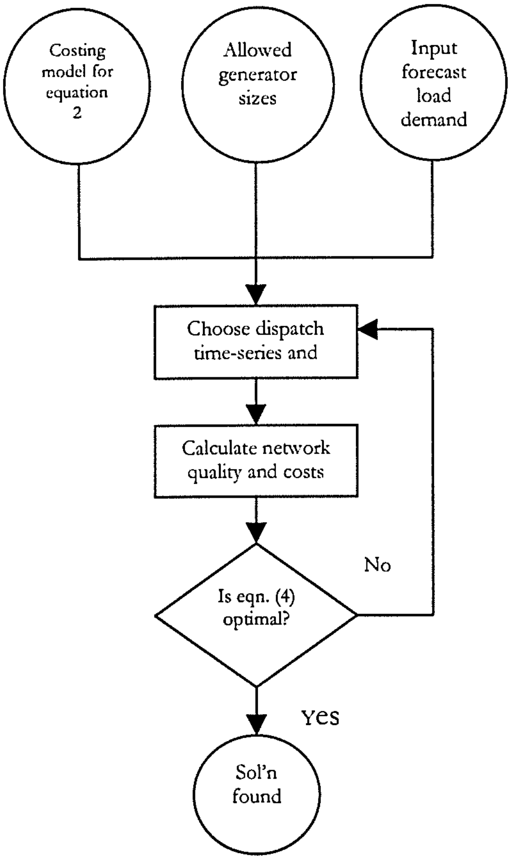

*Figure 2: Process for optimizing for standard power planning from section 2.2*

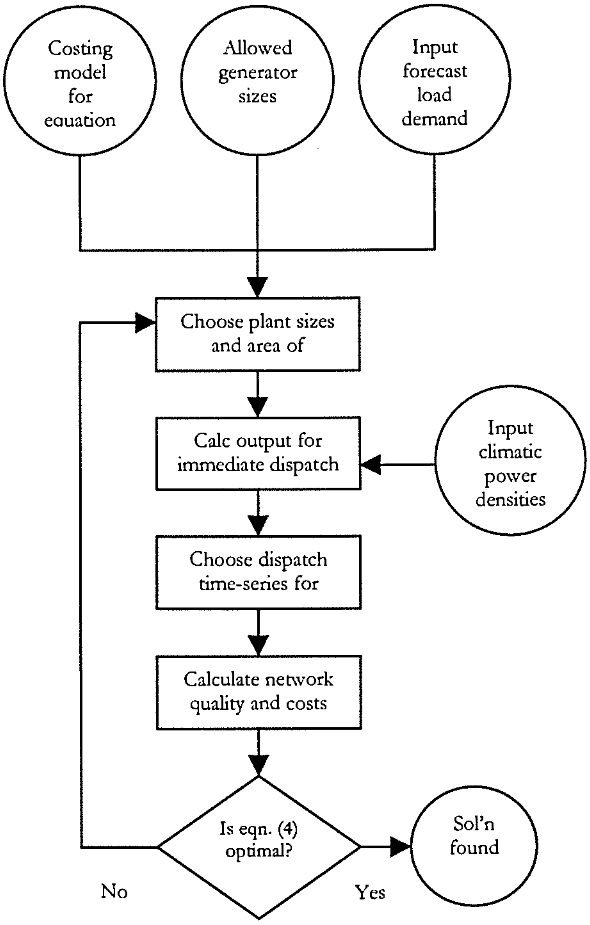

*Figure 3: Process for optimizing for IRES power planning from section 2.3*

This chapter showed how the planning methods changed between power generators that have deterministic and controllable output, and those that rely on stochastic processes for power generation.

The next chapter (Chapter 3) will look into the physical plant modelling for IRES technologies. The physical plant modelling will be put into the overall context of modelling through the LCA framework. The chapter will develop the life-cycle inventory (LCI) template through which IRES technologies can be accurately modelled, and show how the simulation presented in this chapter is embedded into the LCA using goal-attainment.

# CHAPTER 3: APPLYING LIFE-CYCLE ANALYSIS TO RES TECHNOLOGIES

## 3.0 BACKGROUND

Environmental problems are problematic to analyse because of their inherent complexity. Haith (1982) characterizes some of these difficulties, as follows:

> "The management of environmental problems is a challenging venture. These problems involve land, water, air and energy resources that significantly affect human activities and attitudes. A major difficulty is that individual parts of environmental problems function together to produce unwanted results. For example, the water pollution associated with a wastewater discharge to a stream is related to many factors: waste sources and properties, waste collection, treatment process, method and location of discharge, transport of the wastes in the stream, and the effects of the wastes on biota and human use. Each component can be and often is analysed separately, but a water pollution problem results from the interactions of the collective effects of a water pollution *system*."

The LCA attempts to unravel some of the analytic complexity of environmental systems through a systematic approach which breaks down the problem into a number of stages and by attempting to attain two basic goals:

(i) Characterizing the system by a "cradle-to-grave" approach

(ii) Ensuring simplicity and transparency in the methodology

The *cradle-to-grave* approach attempts to define the system boundaries of a production system in what is termed a process model. The system begins at the raw material extraction from the earth and terminates at the point(s) at which the materials are returned back to the earth as either emissions or disposal at the end of the product's useful life. In the LCA, this method of inclusion of upstream and downstream processes in the product life cycle is sometimes referred to as *internalizing externalities*. This is a highly complex view of a production system because it must account for not only the upstream processing of raw materials and sub-components of the product, but also the downstream consumer use, confluence of sub-products into primary products, and the eventual product disposal. To add to this, much of the time multiple product streams must be evaluated in even simple products. For instance, a cradle-to-grave view of an electric lamp would need to assess the cradle-to-grave systems for light bulbs, electric cords manufacture, and possible glass or textile manufacture for the cosmetic aspects of the lamp. This approach can be onerous and seem over-complicated, but it allows for a reasonably unbiased and standardized framework where highly disparate products can be reviewed and compared.

The LCA uses the cradle-to-grave system by first accounting for energy and material inputs and outputs at each stage of the product's life and then conducting analyses on these results. Simplicity and transparency is maintained through a rigorous and systematic accounting procedure, which allows for straightforward auditing of the study and ascertainment of how particular figures were calculated. For environmental problems, complex systems must be clearly delineated for external review (e.g. legal and environmental auditing). In addition, the communication of the results must be understandable when there are often multi-disciplinary decision-makers.

| Stage | Major Activities |
|---|---|
| Goal Definition | • Determine study deliverables and quantifiable goals<br>• Restrict products and processes under investigation |
| System Scoping | • Determine system and process model boundaries<br>• Determine system components that are considered beyond system scope |
| Inventory | • Accounting of materials and energy at each step of process<br>• Include only significant material consumption in overall appraisal according to weight, toxicity, price, and goals<br>• Detail sources used for data gathering<br>• Assumptions to system dynamics and performance |
| Impact Assessment | • Assess inventory and relate to environmental effects<br>• Use indices to asses environmental burdens and system performance |
| Improvement | • Use goals and impact assessment results to determine possible prescriptions for improvement of system |

*Table 5: Summary of the LCA stages and their associated activities*

The LCA consists of five main stages of inquiry; (i) goal definition, (ii) system scoping, (iii) inventory, (iv) impact assessment, and (v) improvement [Vigon, 1993]. Table 5 (above) shows the main activities that are conducted through each stage. *Goal definition* pertains to focusing the study around the measurable goals and deliverables of the overall study. *System scoping* looks at developing the process model and deciding which stages of the system are included in the study and which stages are beyond the scope of the overall study. The *life-cycle inventory* (LCI) is the accounting of materials, energy and other metrics (such as natural resources like land) within the process model. The results of the LCI show where relative consumption of resources are concentrated and rates at which consumption occurs.

From these results, impact assessments are made. *Impact assessments* are typically measures or simulations, which help to define the environmental burden or societal effect of the system in terms relative to the overall goals of the study. Finally, the impact assessment and the LCI are used to determine possible *improvements* in the system. This could take the form of comparing different processes or finding the component(s) in a system that are most likely to provide the greatest benefits through revision of the component(s). As an aside, originally only the latter three stages (inventory, impact assessment and improvement) were prescribed stages, but in order to have the studies more focused, the stages of explicitly defining goals and system scope were added.

Sections 3.1 to 3.7 will outline the life cycle analysis framework through which an IRES network may be analysed. The outline will include some of the general issues in the various stages of the LCA studies. Section 3.1 begins by introducing some terminology and the remaining sections expand on the major concepts for each stage.

## 3.1 DEFINITIONS OF SELECTED LCA TERMS

The following terms are some definitions of common system components of the LCA.

| | |
|---|---|
| *Templates:* | A guide used by analysts for collecting and organizing data. The template describes a material and energy balance for a defined system. It includes resource requirements, transportation requirements, and emissions and waste for that system or subsystem. |

*Input:* Inputs to a process stage are either raw materials, or intermediate products. Thus, into any single stage there are usually multiple material inputs.

*Product:* The output of a process stage that is passed on to following process stages is the product of the stage. It is the input material(s) finished form after undergoing processing.

*Co-products:* After materials have undergone the processing of a stage, the result is a desired product(s) which is then passed on or "flowed" into the following stage of the process. In some process stages, instead of generating waste from the process, materials not used to make the desired product are used to create a product which leaves the overall system, but is used in some other process. These other products which are useful but leave the scope of the current system are the co-products to a process stage.

*Emissions:* A material flow within a process in which the flow goes directly from the process stage to the environment, or, in other words, out of the overall system boundaries. The sink for the emission is the eco-sphere into which it flows. The three major emission types that are considered are air-borne, water-borne, and solid (landfilled/land-based sequestration) emissions.

*Cradle-to-gate:* The representation of a subsystem in an overall process flow where the results of previous LCA studies are used to quantify and characterize the subsystem. These previous LCA results are integrated into the overall LCA system's results. This takes advantage of the re-usability and data sharing that is possible for certain processes (such as the production of steel or other widely used intermediate products).

## 3.2 GOAL DETERMINATION

The product of the goal determination stage should make clear the purpose and scope of the study. This requires the definition of both the study deliverables and the constraints under which the study is conducted.

The purpose of a study is usually a combination of issues pertaining to:

(i) Product design

(ii) Setting industrial or governmental policy

(iii) Environmental system assessment

The product design study may be summarised under two main areas of concentration. The first is to use the LCA to identify stages within the life cycle of a product or process where a reduction in resource use and emission might be achieved. The second is to compare the system inputs and outputs in order to compare the performance between alternative products, processes or activities. Setting policy is focused on determining general guidelines and procedures to foster desired environmental performance within the system(s). Environmental system assessment studies attempt to establish a baseline of information on a system's overall resource use, energy consumption, and environmental loading.

The constraints that should be stated at this stage of the study are the time for conducting the study, operating budget and the informational availability/requirements of the project.

| **Attributes of Study** | **Typical attributes of item** |
|---|---|
| Specific area of study | Product or process under investigation |
| Organization Type | Public, Private, Public-Private Disclosure |
| Purpose(s) of study | Product design, setting policy, system assessment |
| Constraints of study | Time of study, Budget, informational |
| Deliverables | Reports, analysis tools, environmental performance |

*Table 6: Study classifications and some clarifications to ascertain biases therein*

The goals of the study are to help focus the exercise by giving direction on how information and data are processed, to determine methods for producing the final deliverables and to communicate the overall results.

## 3.3 SYSTEM SCOPE

From Vigon (1993), a general "cradle-to-grave" system has four stages; namely raw materials acquisition, manufacturing, use/re-use/maintenance, and recycling/waste management. Figure 4 (below) shows the general system relationships.

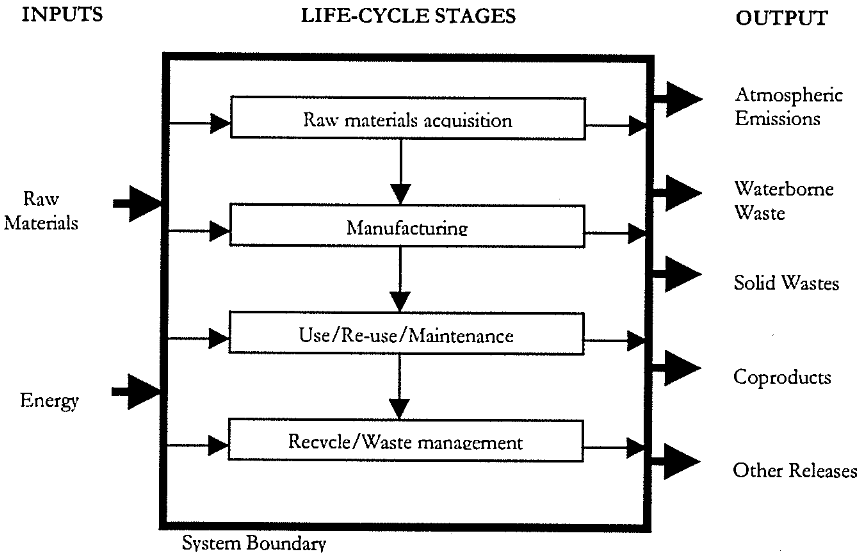

*Figure 4: Defining system boundaries, Source: Reproduced from [Vigon, 1993]*

For power generation systems, the general model of figure 4 may be adapted to reflect some of the realities that exist in these particular systems. Power generation systems have many irregularities in their manufacture, use and disposition. One of the other difficulties with these systems is that within a network of power stations, different power generation technologies may be employed. In addition, the timeframes under which these facilities are constructed, operated and disposed of is highly independent to the technology.

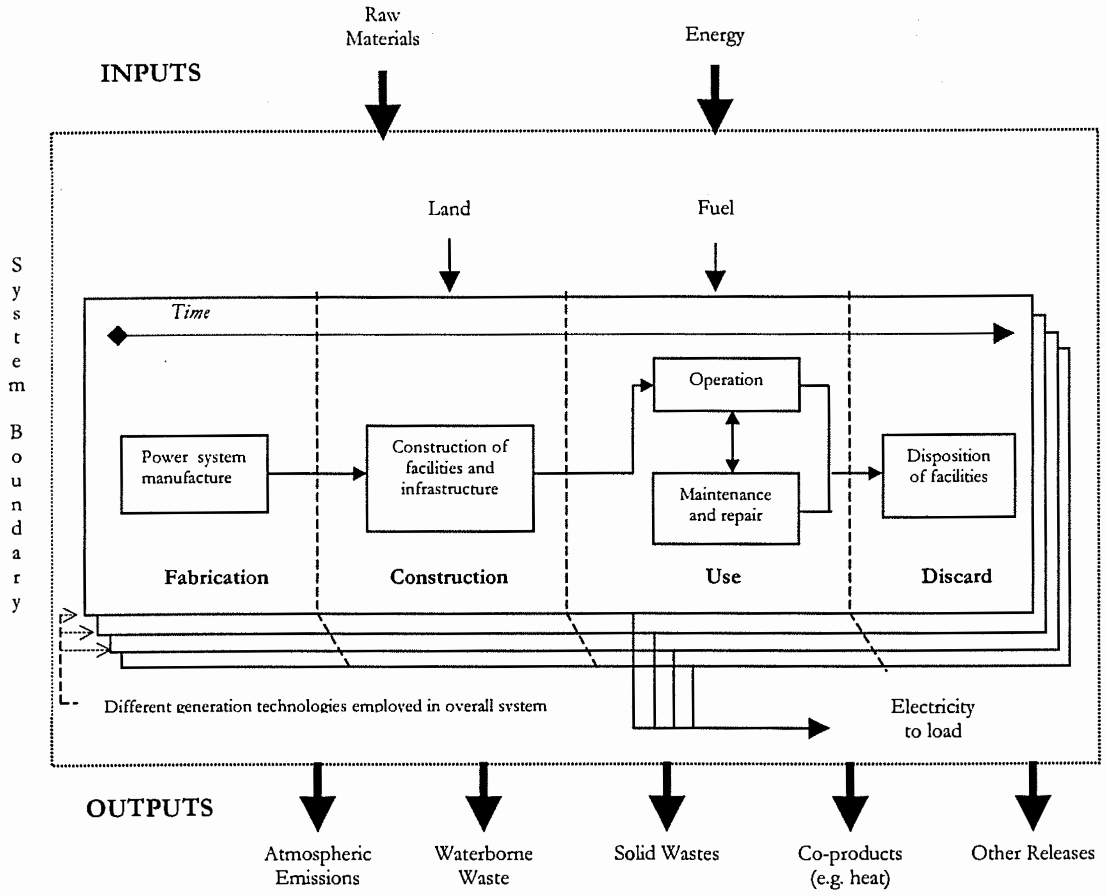

*Figure 5: System boundaries of single-load electricity power networks*

Figure 5 presents some of the specifics to power generation network's life cycles. Figure 5 shows that the overall system is made up of a number of full life-cycle subsystems. They all share the same effluent and input streams for system assessment. But each generation technology undergoes different manufacture, construction, operation and disposition. In the figure above, the heavy vertical arrows show material and energy streams that exits in all stages of the electricity generation process. The thin arrows within the system show inputs which are relevant to this study and that occur at only particular stages in the process. The vertical dashed lines divide the process(es) into discrete stages. Across the stages, there are three system boundaries that must be addressed in order to define the system. These are the process or stage, temporal and spatial boundaries of the system.

### Process Boundary

The general process of generating electricity includes all upstream activities such as the raw materials acquisition in both fabrication of components and the construction of the plant and required infrastructure.

Operating costs in acquiring and consuming fuelstocks must be addressed for each technology in the overall power grid. This translates to accounting of transportation, storage, procurement and processing of fuels.

At the end of the downstream processes, the disposal of generating facilities must be considered. The process boundary looks at the material and energy requirements of haulage, landfills and recycling.

## Temporal Boundary

The timeframes in power generation systems have a lot of variation. For a typical hydro or nuclear power plant project, it can take over a decade to go from proposal to construction to operation of the plant. In contrast, for a wind farm, relatively large installations (on the order of 50MW) can be installed and be operating within a year. Thus, in assessing the life-cycle effects of integrated power systems one must clearly delineate the lifetimes and stage timeframes of the different technologies. These issues highly affect performance because the power per unit material is strongly related to the equipment lifetimes, and the useful operating lifetime of the facility. Additionally, monetary costs can be highly skewed if decommissioning and discardment charges (which again are strongly related to time for hydro and nuclear power) are not properly accounted for.

Other temporal issues arise in assessing the operation of the plants. These include examining the frequency of maintenance and repair. For thermal and backup power systems, another issue is the availability and transport of fuel, especially for biomass systems because the system may not be able to supply the rate of fuel consumption needed for optimal performance.

Finally, in decommissioning power plants, one of the temporal issues is the short and long-term effects and possible remediation services that are concomitant with shutting down a facility.

## Spatial Boundary

The renewable technologies studied in this report all utilize highly diffuse power sources. The sun, wind and biota require not only land but also properly situated land. Thus, one of the difficulties in assessing the performance of these systems is the constraint of the local resource of land. The location of these facilities is very important to achieving predictable performance. Two general issues must be dealt with specifically for IRES analysis, (i) availability of land, and (ii) suitability of geographic characteristics (climatic and landform) for energy conversion systems. A third land issue for power generation systems is the distance for transmission and distribution (T&D) of power within the service domain because the efficiency of the whole network is affected by the T&D losses. The three boundary types reviewed are summarized below in Table 7.

| **Boundary Type** | **Boundary descriptions** |
|---|---|
| Process | *Manufacture of power conversion equipment*<br>Construction of power plant and additional infrastructure<br>Use of power plant and emissions from generating energy<br>Disposal costs in haulage, landfill, and recycling |
| Temporal | Useful operating lifetime of equipment<br>Frequency of maintenance and repair<br>Availability of fuelstock<br>Timeframe for facility passing from manufacture stage to disposition stage |
| Spatial | Availability of land<br>Suitability of climate and landform for energy conversion systems<br>Distance to transport power from power plant to load demand site |

*Table 7: Summary of boundary types in power generation systems*

## 3.4 INVENTORY OF MATERIALS AND ENERGY FOR RENEWABLE TECHNOLOGIES

Inventory calculations fall into the three main classifications; (i) fixed inventory, (ii) variable inventory, and (iii) recycled inventory (table 8). Each of the three has certain properties that must be adhered to in order to properly and accurately assess the overall inventory. Fixed inventory are material flows that may be accounted through the life cycle of a single unit of product and then simply scaled in magnitude to the number of units of product in question. Variable inventory is different in that it is not a factor of the number of units of products but rather the rate of inventory inclusion. It is usually dependent on a timeframe and the number of units in question. Recycled inventory is the amount of material that is re-directed from the discarding of a product to a new product stream. Recycling of materials is done in two main ways. The first way, which is known as *open-loop recycling*, consists of taking the materials from one product and re-processing some of the discarded product's materials and using them within a different type of product. The other way of recycling is called *closed-loop recycling* because the recycled material is used in the manufacture of the same product line. Both of these methods potentially reduce raw material use but their effect on a system is not always straightforward. As a consequence, they must usually be quantified by functions that use the time, magnitude of material flow and open- or closed-

| **Inventory** | **Units** |
|---|---|
| Fixed inventory | Weight/Unit |
| Variable Inventory | Weight/Unit-time |
| Recycled inventory | Weight/Unit-time |

*Table 8: Summary of inventory classifications*

loop process systems to calculate the appropriate credits to the inventory.

## 3.4.1 USING TEMPLATES FOR SYSTEMS ANALYSIS

The goal of the life-cycle inventory (LCI) may be summarized as a report of the material, energy, and resource flows into and out of a "cradle-to-grave" system boundary. A useful tools to conduct the LCI is the template. Figure 6 shows one of the most widely used templates, which was proposed for manufactured products by Franklin and Assoc., Ltd. [Vigon, 1993].

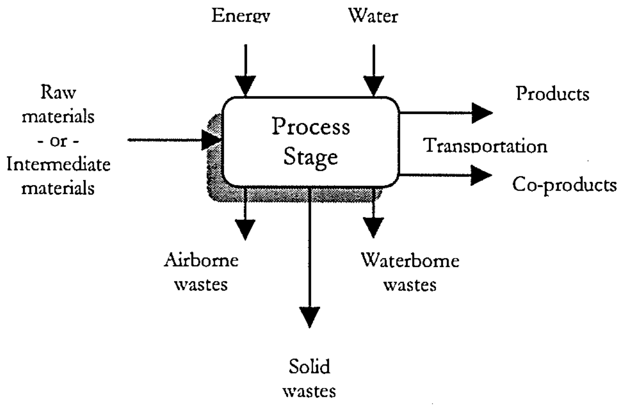

*Figure 6: Proposed LCA template from Franklin & Assoc., Ltd.*

A template can be thought of as a general framework in which parameters to the system can be classified and through which a rational accounting between process stages can be made simpler.

The template from figure 6 can be generalized to other systems as general flows of material and energy. Figure 7 shows the general flows. Material inputs are defined as the materials used directly in the process stage. Cascaded flow has two classes of items; (i) useful output which gets passed on to successive stages (products and co-products), or possibly to the system boundary when the product is discarded, and (ii) the resource expenditure in having the process proceed from one stage to another (such as transportation costs). Local resources refer to finite or constrained resources, which are applied or used by the process, such as water, land, labor, or energy that are geographically local to the process stage. Appropriated resources from another region within the system scope should be accounted for in the process stage of procurement of that resource, otherwise embodied measures to the process stage may be made, but these should be highlighted with explicit reasoning. Finally, emissions to the system boundary may be considered as discharges of waste products directly into some ecological sphere (e.g. geosphere, hydrosphere, biosphere, atmosphere).

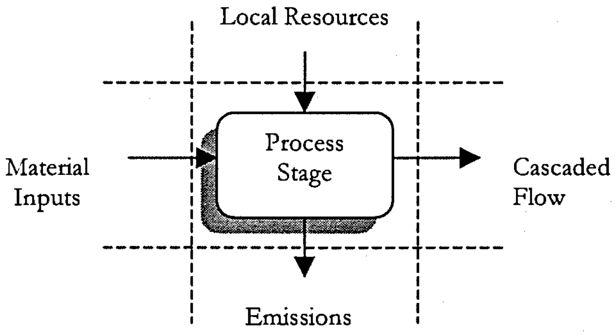

*Figure 7: Generalized LCA template for a process stage*

The following sections develop a template for the life-cycle of a general electricity conversion facility (such as a solar PV array or wind turbine).

### 3.4.2 FABRICATION

Plant specifications should summarize the manufacturer's classification of the technology in question. It should provide enough information so that the source of specifications within the LCA may be traced. An example of manufacturer's plant specification is provided in Table 9.

| | | | |
|---|---|---|---|
| **Type of Technology:** | Basic description (e.g. WEC, Coal-fired boiler, hydropower) | | |
| **Manufacturer:** | Company Name | **Model No.:** | |
| **Fuel Type:** | | **Unit Size:** | Peak power output |
| **Cogeneration:** | YES/NO | **Max. load factor:** | |

*Table 9: Plant Specifications Template*

The material acquisition inventory should separate the plant into components and processes. Each component and process should then be assessed for direct material and energy inputs. An example of the major components of a photovoltaic cell is shown in Figure 8. This information is usually available through general manufacturing processes and manufacturer specifications.

Table 10 shows an example materials acquisition inventory template. Beyond the components and the constituent materials of the components, the three material qualities of particular material should be included in the analysis. Only the information relevant to the study need be included in the final analysis, thus there will almost certainly be elements of the material inventory that will not have values.

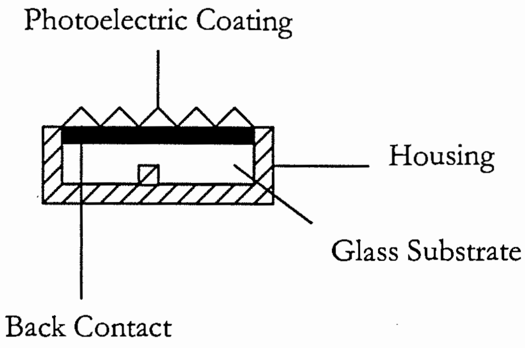

*Figure 8:* *Components in a single photovoltaic cell*

| **Component Name** | **Materials** | **Toxicity** | **Price** | **Weight** |
|---|---|---|---|---|
| | | | | |

*Table 10:* *Material Acquisition Inventory Template*

Emissions from the fabrication stage should include embodied energy and waste material that are in the direct material and energy flows for the various components and processes. The meanings of each column have been included in Table 11.

| **Material** | **Process** | **Emission** | **Discharge Type** | **Effect** | **Rate** |
|---|---|---|---|---|---|
| Inventory source material of emission | Process model source of emission | Chemical description of emission | Eco-sphere to which the emission is passed | Harmful or significant effects of emission | Rate of emission, usually in units of weight/time |

*Table 11:* *Emissions Summary Template*

## 3.4.3 CONSTRUCTION

This stage should define the siting rules around which the technology may be planned and deployed. This information is usually made available in practitioner's guides and manufacturer recommendations.

In general, the land requirements of facilities should entail the required infrastructure, land type(s), land area and the distance between the load and power generator. For specific cases, other information such as land use changes, regional availability of land, and existing infrastructure should also be assessed.

| | |
|---|---|
| **Region:** | Proposed location of installation |
| **Land Area Required:** | Per unit install land requirements |
| **Land Definition:** | Suitability criteria for siting facility |
| **Required Infrastructure:** | Access roads, T&D systems, water diversions |
| **Distance to Load:** | Distance that power must be transmitted to reach load |
| **Regional Effects:** | Regional land use changes |

*Table 12: Land Requirements Template*

As in the fabrication stage, the structural components and processes of construction should be outlined similar to Table 10. The facility inventory (Table 13) should summarize the construction stages, facility components (e.g. foundations, roads, housing), and the materials summary and energy required for erecting the facility.

| Construction Stage | Facility Part | Material | Weight | Toxicity | Price |
|---|---|---|---|---|---|
| | | | | | |

*Table 13: Facility Inventory Template*

The material and energy flows of the facility may then be assessed for embodied waste streams and energy. The construction stage emissions table (Table 14) has the same structure as Table 11 used in the fabrication stage, but it is applied to the emissions from the materials and processes outlined in Table 13.

| Material | Process | Emission | Discharge Type | Effect | Rate |
|---|---|---|---|---|---|
| Inventory source material of emission | Process model source of emission | Chemical description of emission | Eco-sphere to which the emission is passed | Harmful or significant effects of emission | Rate of emission, usually in units of weight/time |

*Table 14: Emissions Summary Template*

### 3.4.4 USE

This section typifies the use or activity of electricity generation. Table 15 examines the temporal aspects of power generation. Time issues are usually quite different for different technologies. Reliability and system degradation are both temporal issues. These go beyond the scope of this report, but in practice they play significant roles in the efficiency of most power systems.

| | |
|---|---|
| **Time to complete construction** | Amount of time from beginning to end of construction phase |
| **Time to begin generating power** | Time from after construction has begun, that facility may start generating power. If it cannot generate at full capacity at the beginning of power generation activities then details should be provided as to the magnitude of load that it will be able to service. |
| **Useful life of plant** | Time over which the facility is used for the purpose of generating electricity |
| **Rate of degradation of plant services** | Rate(s) of plant degradation through useful lifetime |
| **Backup Facilities** | Type of backup facilities in the plant such as batteries or a pumped water system. This is not the power network backup facility. |
| **Maintenance Effects on Power Output** | Schedules or rates of required system maintenance that would effect the power output, or that would add to the inventory of the plant |

*Table 15: Time Issues Template*

The power output from the plant must be clearly specified, in order to achieve accurate data-models of power efficiency relative to material inputs. The power output template, in general, should provide enough information to set up the architecture of the high-level simulation environment for the particular technology. Table 16 contains power output information that is not complete, but is typical.

| **Dispatch Characteristics** | Immediate off-load, short-term governing, long-term scheduled |
|---|---|
| **Offloading Capacity** | *Type and magnitude of offloading capability* |
| **Power Type** | AC or DC |
| **Maximum Current** | |
| **Maximum Voltage** | |
| **Maximum Power** | |
| **Rated Load Factor** | |
| **Grid-connected** | Yes/No |

*Table 16: Example Power Output Template*

The following two tables (Table 17 and Table 18) should characterize the normal operating condition inventory of materials. These tables are filled in the same as those fabrication inventory templates introduced in Table 10 and Table 11, respectively. The difference is that these values will usually be rates of consumption as opposed to per plant emissions (i.e. variable versus fixed inventories).

| Activity | Material | Toxicity | Weight | Price |
|---|---|---|---|---|
| | | Report values as rates used during operation | | |

*Table 17: Operation Inventory Template*

| Material | Process | Emission | Discharge Type | Effect | Rate |
|---|---|---|---|---|---|
| | | | | | |

*Table 18: Emissions Summary Template*

Conspicuously missing in this section was the characterization of facility reliability and abnormal operating conditions. These issues are highly relevant to power systems analysis but because of time and resource constraints they were beyond the scope of this work.

### 3.4.5 DISPOSAL

Disposal is the stage in which the facility is no longer useful for its intended purpose of power generation. The modes in which materials are discarded are recycling, re-use, and emissions. The introduction to this section introduces the concepts of open-loop and closed-loop recycling. Efficient recycling and re-use of materials usually produces a credit for inventories. But, the effects of recycling are still active areas of LCA research.

Table 19 and Table 20 summarize the emissions and effects of recycling. One of the caveats to the emissions table (Table 20) is that at this stage it should include effects such as hazardous waste disposal and incubation of irradiated materials. Again, this is still an active area of research in LCA studies.

| Material | Mode | Processing | Costs | Time to dispose |
|---|---|---|---|---|
| | | | | |

*Table 19: Summary of Material Processing Template*

| Material | Process | Emission | Discharge Type | Effect | Rate |
|---|---|---|---|---|---|
| | | | | | |

*Table 20: Emissions Summary Template*

## 3.5 IMPACT ASSESSMENT THROUGH ENVIRONMENTAL INDICATORS

Assessing the impact of multimedia effects and multi-chemical reactions and flows necessitates the use of some methodology that is both understandable and accurate. The modelling and measurement of specific physical effects of pollution are beyond the scope of this thesis. In this study, the impact assessment is simply the creation of a set of expressions, which provide quantitative measures of system success from different viewpoints. In practice, a more reasoned approach would be the use of environmental indicators. Environmental indicators are vectors of quantitative factors that contribute to a particular class of environmental problem. The vector is then made into an indicator by applying a weighting scheme to the different factors in the vector and an overall indicator or measure of the environmental burden is thus made.

Indicators are still an active area of research which should help to simplify the complex systems that characterize environmental problems. Issues such as global warming, deforestation, habitat encroachment, and ground water pollution, are all environmental problems that are caused by complex reactions between multimedia emissions from various human-based endeavours. The World Resources Institute recently published "Environmental Indicators: A Systematic Approach to Measuring and Reporting on Environmental Policy Performance in the Context of Sustainable Development" [Hammond, 1996]. The paper summarizes the type of information criteria that they envision for the development of environmental indicators.

The purpose for any numeric indicator is to both quantify information so its significance can be made apparent, and to simplify information for complex phenomena so laypersons may more easily understand the dynamics of the system. Environmental indicators are always based on some empirical model of the phenomena under investigation. The indicator represents the system's performance in relation to the indicator's underlying model, not necessarily the actual performance of the system under analysis. Thus, the theory is that the indicator should allow the comparative analysis of different systems by simplifying the environmental performance of a system to a numeric value.

In choosing candidate environmental indicators, [Hammond, 1996] acknowledges three major indicator design characteristics which have proven to produce the best set of indicators:

| | |
|---|---|
| User-driven: | Indicator is relevant and meaningful to the intended audience |
| Policy-relevant: | Indicator reflects policy concerns |
| Highly Aggregated: | Indicator should have as few indices as possible without sacrificing accuracy and relevance |

The OECD and UNEP have been jointly working on a framework for developing environmental indicators. The table below shows a small subset of the indicators, which are currently under consideration. The indicators have been grouped according to different stressor types. Indicators of pressure on the environment are measures of pollution and resource depletion. The state indicator attempts to characterize the state of the environmental subsystem that is being affected. Finally, response indicators are seen as measures of the intensity of change from either the eco-system and/or human feedback on the environmental system.

| Issues | Pressure | State | Response |
|---|---|---|---|
| Climate Change | (GHG) emissions | Concentrations | Energy Intensity; Env. Measures |
| Acidification | ($SO_x$, $NO_x$, $NH_3$ ) emissions | Deposition; concentrations | Investments; signatory agreements |
| Biodiversity | Land conversion; land fragmentation | Species abundance vs. virgin territory | Protected areas |
| Soil Degradation | Land use changes | Top soil loss | Rehabilitation/ protection |

*Table 21: Proposed environmental indicators from the OECD and UNEP*

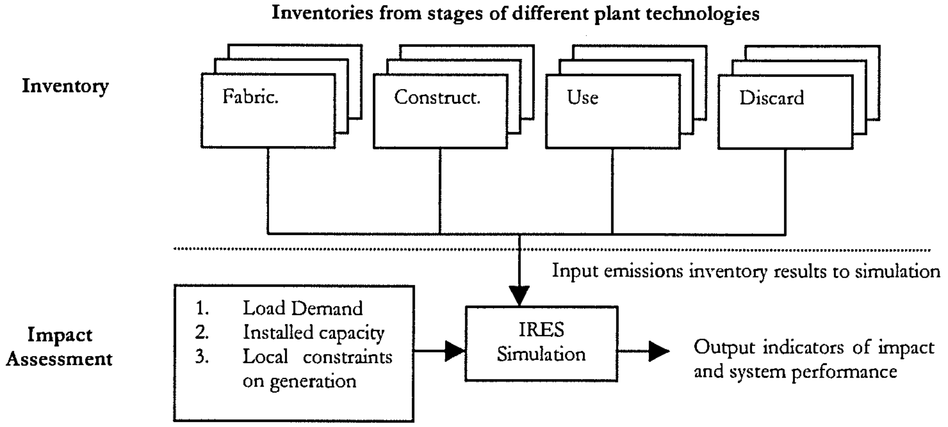

*Figure 9: Calculating indicators within impact assessment*

For the impact assessment, once an indicator(s) has been chosen then it becomes a matter of conducting the LCI and converting units to suitable quantities for the indicator. Figure 9 shows the process for calculating a pollution indicator from the LCI and using a simulation-based data model for an IRES.

## 3.6 SYSTEM IMPROVEMENT

System improvement is the LCA stage in which the impacts and inventory results are analysed in order to ascertain the way to improve the system performance. System improvement for energy systems may be defined from economic, environmental, social, or thermodynamic criteria, and any combination thereof. The criterion for what constitutes a successful system was presumed to have been determined within the LCA goal definition stage. Quantitative expressions for measuring system success would then have been developed in the impact assessment. System improvement investigates the limits of feasible policy and design boundaries.

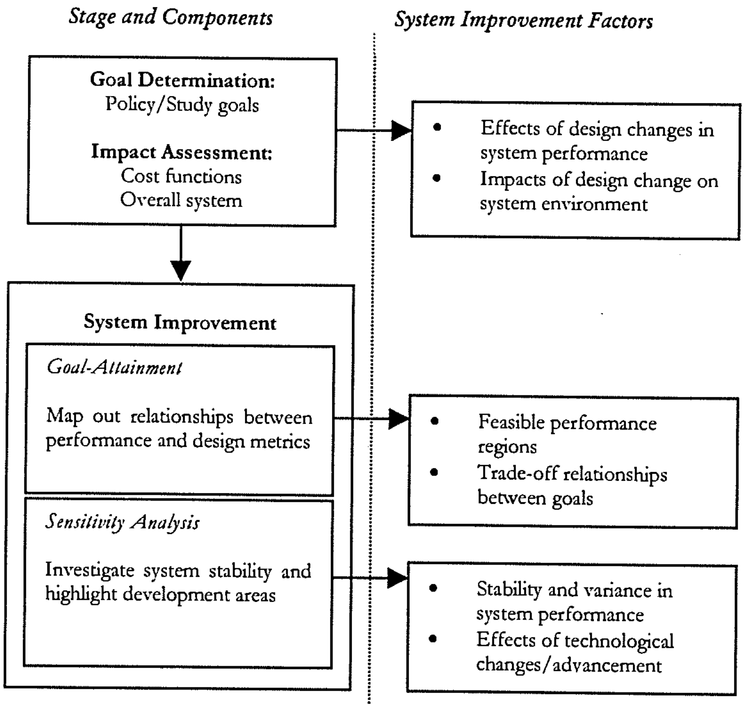

*Figure 10: Summary of LCA components used to determine system improvements*

In determining means and methods for system improvement, there are many analytical tools that are available. In this study, the system improvement stage of inquiry is conducted via a goal-attainment system and a simulation framework. This improvement system is meant to discern suitable performance regimes. The feasibility of a quantitative performance-based policy can be confirmed by using goal-attainment to find that an appropriate design exists. Figure 10 summarizes the factors and components used to test and determine system improvements.

In general, goal-attainment for the power balance optimization presented in section 2.3 may be viewed as a modification of the minimization represented in equation 2.5, which has been reproduced below.

$$\min C \quad s.t. \quad (2.1a),(2.1b),(2.1c),(2.1d),(2.3) \quad are \quad satisfied \qquad (2.5)$$

Equation 2.5 contains a C which represents a cost function for the overall power balance. In goal-attainment, *G* is introduced, which is the target cost for the function. One of the simplest methods for finding a feasible design for a particular least-cost target is to minimize the function *C-G*. [Matlab, 1998]

$$\min |C-G| = 0 \quad s.t. \quad (2.1a),(2.1b),(2.1c),(2.1d),(2.3) \quad are \quad satisfied \qquad (3.1)$$

For this study, a goal-attainment system was written in the Matlab mathematical software environment. In general, the simulation system uses the models presented in Chapter 5. In the table below, the general stages of execution, functionality and data sets are summarized for the goal-attainment system considered in this thesis.

| Stage | Activity | Output |
|---|---|---|
| *Data Acquisition* | 1. Required data sets:<br>- Load demand<br>- CWEC climate data for site<br>- Manufacturers' specifications for energy conversion technology<br>2. Read CWEC and extract time-series for wind, insolation and temperature<br>3. Calculate power densities for solar, wind and biomass catchments | 1. Per unit design variable energy catchments for:<br>- Wind<br>- Insolation<br>- Biomass harvests<br>2. Load demand |
| *Pre-processing* | 1. Configure system to use appropriate cost functions and cost values<br>2. Initialize Matlab environment for global variables and output buffers<br>3. Read stored energy catchment time-series<br>4. Read stored load demand | |
| *Simulation* | 1. Run REOS with desired design, pre-processed energy catchment and given load demand | Energy generation from installation:<br>1. Immediate dispatch for:<br>- Wind turbines<br>- Solar photovoltaics<br>2. Short-term dispatch with fuel storage:<br>- BIG/GT<br>3. Unserved load |
| *Goal-attainment and optimization* | 1. Choose appropriate mix of cost functions (or constraints) for optimization or goal-attainment from:<br>3. Production cost of power in $/kWh<br>4. Life-cycle $CO_2$ emissions in kg $CO_2$/kWh<br>5. Land area required for regional and sustainable power generation<br>6. Percentage of load that may go unserved by final design<br>2. Determine desired performance targets and possible design constraints, and convert per unit power generation metrics ( $/kWh, kg $CO_2$/kWh) to life-cycle metrics (total $ over and total $CO_2$ emissions over simulation period)<br>3. Combine simulation, cost functions, pre-processed data sets and either Matlab 'attgoal' or 'constr' functions to conduct design search using constrained SQP-optimization routines | 1. Output design and performance of searched-for system |

*Table 22: Implementation of the RES goal-attainment system*

## 3.7 SUMMARY OF THE LIFE-CYCLE ANALYSIS FOR IRES

This chapter introduced the LCA methodology and its concomitant stages. Each of the stages were presented for applying the LCA framework to power system networks. Tables 8 to 20 were presented as a possible template for studying the materials inventory for the facilities of a power network. This section introduced the general framework around which the overall study of this thesis will be conducted.

The following chapters (ch.4 and 5) will conduct an LCA for a simulated IRES planning exercise for two Canadian sites.

# CHAPTER 4: LIFE-CYCLE INVENTORY OF RENEWABLE TECHNOLOGIES

## 4.0 INTRODUCTION

The following sections outline the life-cycle inventories for specific renewable electricity generation technologies. The life-cycle assessment begins with the determination of the goals of this study (sect. 4.1). The system scope is then defined (sect. 4.2). Following the goal determination and system scoping stages, the life-cycle inventory results are presented (sect. 4.3-5). These use the templates developed in chapter 3. Each technology inventory begins with a general description of the process to manufacture, use and dispose of the power station. This includes notable emissions and effects. The results are summarized at the end of each section. In addition, specific commercial technologies have been selected to demonstrate how they may be used in the LCI.

One of the major assumptions used in the inventories was that there would be no backup facilities for the individual power generators such as batteries or pumped water systems. Instead, this study in IRES assumes that the distributed power generators are inter-connected onto a shared bus, and that offloaded power will be handled via the grid.

The study was conducted using only existing literature, both general figures published in other studies and manufacturer specifications. The process flow diagrams used consisted of very coarse descriptions of the actual processes. This was done due to time and resource considerations. One element that is conspicuously missing in the emissions summary tables (tables 23, 24, and 26) is the effects of discarding of power stations on emissions. This was done because of time considerations. In addition, access to commercial LCI databases that would detail many of the common steps (e.g. two of the most popular databases would be Ecobalance, Inc.'s DEAM database, or the Swiss Office of Forestry and the Environment's BUWAL database) were not available for the most up-to-date numbers [DEAM,1997], [BUWAL,1998].

Economic considerations were taken from two sources. The first was from the software libraries of Hybrid2 [Hybrid2, 1997]. Hybrid2 modelled IRES networks and was used extensively in the validation of the REOS model. Thus, per unit area installation pricing information for wind turbines and photovoltaic systems were borrowed from the software package. For BIG/GT systems, the LCI study conducted in [Mann, 1996] was used.

## 4.1 GOAL DETERMINATION

The goal of this study is to provide a framework from which further work may be done in order to aid policy-makers make more objective decisions concerning the deployment of renewable energy systems. A dictionary definition of policy is "a definite course or method of action selected from among alternatives and in light of given conditions to guide and determine present and future decisions". To these ends, the goals of this study were:

(i) Demonstrate the use of goal-attainment for attempting to relate performance tradeoffs within a mock IRES system

(ii) Define performance of the electricity network with the three indices of price of electricity, land occupation of the network, and air-borne carbon dioxide emission levels

(iii) Produce a reasonable methodology for determining rules for policy-making using a design model to map system performance

(iv) Use available literature to conduct the study

## 4.2 DETERMINING THE SYSTEM SCOPE USING THE REOS MODEL

An integrated renewable energy system is depicted below in Figure 11. It is based on the renewable energy optimization and simulation (REOS) [Venema & Ali, 1998] model developed at the University of Waterloo.

The system is bounded to a specific geographic region. Within this region are included all the operating facilities for power conversion from renewable technologies. External to the overall system is a long-term power grid backup. The power grid is made external because the electricity that it provides can come from an open market of numerous distant power sources.

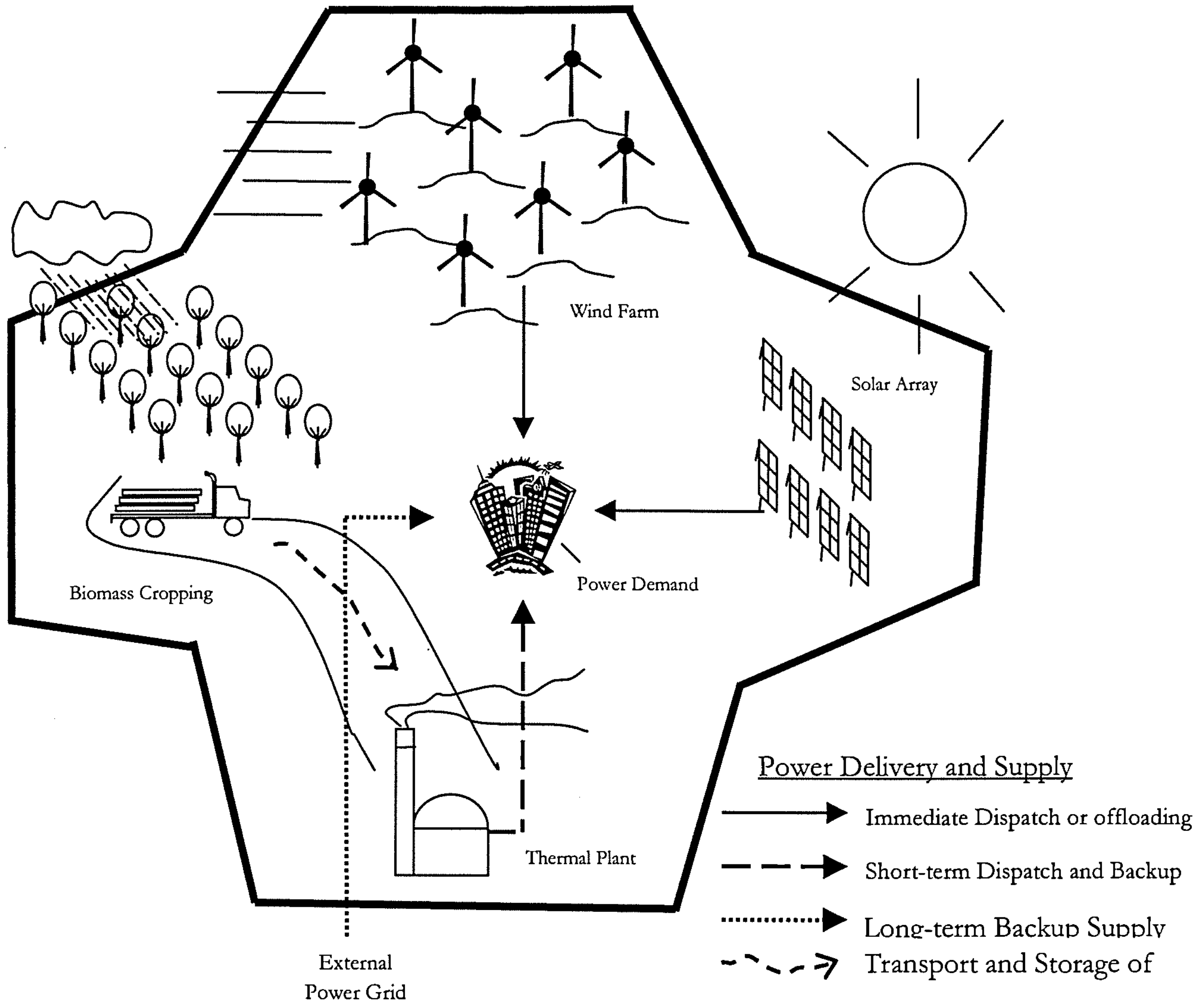

*Figure 11: REOS model of sustainable electricity*

Power delivery is shown as a set of various storage, dispatch and backup schemes. Immediate dispatch power sources must deliver their continuous power output to some load, whether useful or not. Scenarios in offloading energy include routing the excess power to some storage facility (batteries or pumped water), or in cases where an external power grid exists, the excess power is sold on the open market. Short-term dispatch sources do not necessarily output energy continuously and may potentially consume fuel even if the system is kept idle. Short-term dispatch means that load demand can be met variably as needed provided that the supply of fuel for the facility does not run out. Long-term backup facilities may be viewed as sources that provide power on demand with a very low outage probability, but because of cost, environmental effects or other factors, it is the least favoured power source.

The following assumptions were made in this study:

- Long-term backup facilities already exist within the region
- End-use inventory such as factory emissions, or household emissions from electricity use are beyond the scope of this study
- Infrastructure for power delivery over a shared grid already exists (i.e. mature electricity market)
- Discarding of facilities has no effect on material consumption

Transmission and distribution (T&D) infrastructure and end-use activities were not considered within the study because although they are necessary to make a proper energy analysis, the actual processes between of T&D and end-use were seen as independent enough to deem outside of the study scope. Discarding of facilities was not as straight-forward. The main reason for its omission was that suitable literature at the time of this thesis was not available in order to characterize the discard phase for all power types. Thus, it seemed prudent to exclude the discard stage entirely.

Overall the system should include all processes that occur within the regions boundaries, which includes:

(i) Assume that fabrication of facilities is done locally, but raw material transport may be from distant locales

(ii) Electricity demand is completely domestic to the region

(iii) Disregard inventory consumption/emission outside of the simulation timeframe

Thus, the scope of the study should respect the spatial constraints of the simulated region, and consider only emissions within the timeframe of the simulations.

## 4.3 WIND TURBINE MATERIALS INVENTORY

The following sections (4.3.1-6) outline the modelling of the material inventory and power simulation for wind turbines. Sections 4.3.1-4 detail the process stages for wind turbines. Figure 12 in section 4.3.5 summarizes the process model that was outlined in the preceding sections. The results of the materials inventory as applied to the Jacobs 41/500 [Jacobs, 1998] wind turbine is summarized in Table 23 in section 4.3.5. Finally, the power simulation of a wind turbine is shown in section 4.3.6.

### 4.3.1 FABRICATION

The materials used in wind turbine technology are commonplace. These are predominantly steel, concrete and aluminum. The three main components of a wind turbine are the nacelle, rotors and tower. Additionally, modern power conditioning and inversion equipment must be employed to inter-connect turbine power outputs to a shared grid. But, in relation to the overall materials requirements of the system, the power conditioning equipment is a negligible component.

### 4.3.2 CONSTRUCTION OF FACILITY

Typically, a commercial windfarm will use windmills with rotors of 25-50 m in diameter. The towers will be approximately 30 m tall. The overall weight of the structure varies, but for a typical 200 kW installation, it will be on the order of 1-2 tonnes for the rotor, 3-5 tonnes for the nacelle (gearbox and generator) and 7-10 tonnes for the tower. Overall, this works out to an overall weight of 11-17 tonnes for a mid-rated turbine [Nacfaire, 1987]. In order to assemble such structures, there is necessarily a need for road access to the prospective farm area. In addition, land requirements for the spacing between adjacent windmills usually is on the order of 5-10 times the diameter of the rotor [Johansson, 1993]. Finally, the foundation of the tower will add about 20% to the weight of the entire aboveground structure. The foundation is predominantly made of concrete.

### 4.3.3 USE

Electricity generation from a wind turbine is a benign process. There are no direct emissions from the operation and electricity generation. But the system does require maintenance and repairs. The system does potentially require backup and energy storage facilities in times when either load cannot be met by the immediately generated power or when demand is low and the generated power must be offloaded. Backup facilities are usually on-site fossil-fuel based generators, grid connection, or discharge from storage facilities (such as pumped water or battery systems). Systems to offload energy include pumped water systems and delivering energy into a shared heterogeneous power grid. The useful life of modern windmills is on the order of 15-20 years. [Nacfaire, 1987], [Walker, 1997]

### 4.3.4 DISCARD

The emissions from the retiring of facilities emissions will come from transportation of materials to processing plants (typically, recycling or landfill). The materials that are usually recycled include the metals (aluminum, steel and copper) in the nacelle and tower. Concrete, fiberglass and wood are usually landfilled, although the concrete can be re-used as road construction materials.

### 4.3.5 INVENTORY AND PROCESS SUMMARY

Appendix A.1 contains the LCI template for the Jacobs 41/500 wind turbine. The materials inventory calculations for the Jacobs wind turbine is presented in Appendix A.5. The materials summary is shown below in Table 23. Additionally, the process model is depicted in Figure 12.

| **Item** | **Carbon Dioxide Emissions** |
|---|---|
| *Fiberglass* | 12.94 tonnes $CO_2$/unit |
| *Steel* | 308.7 tonnes $CO_2$/unit |
| *Copper* | 7.7 tonnes $CO_2$/unit |
| *Aluminum* | 1.41 tonnes $CO_2$/unit |
| *Cement* | 15.7 tonnes $CO_2$/unit |
| *Transport* | 0.275 tonnes $CO_2$/unit |
| *Total Fixed $CO_2$:* | 346.725 tonnes $CO_2$/unit |
| *Total Variable $CO_2$:* | 0 tonnes $CO_2$/unit |

*Table 23: Summary of Jacobs 41/500 wind turbine carbon dioxide emissions*

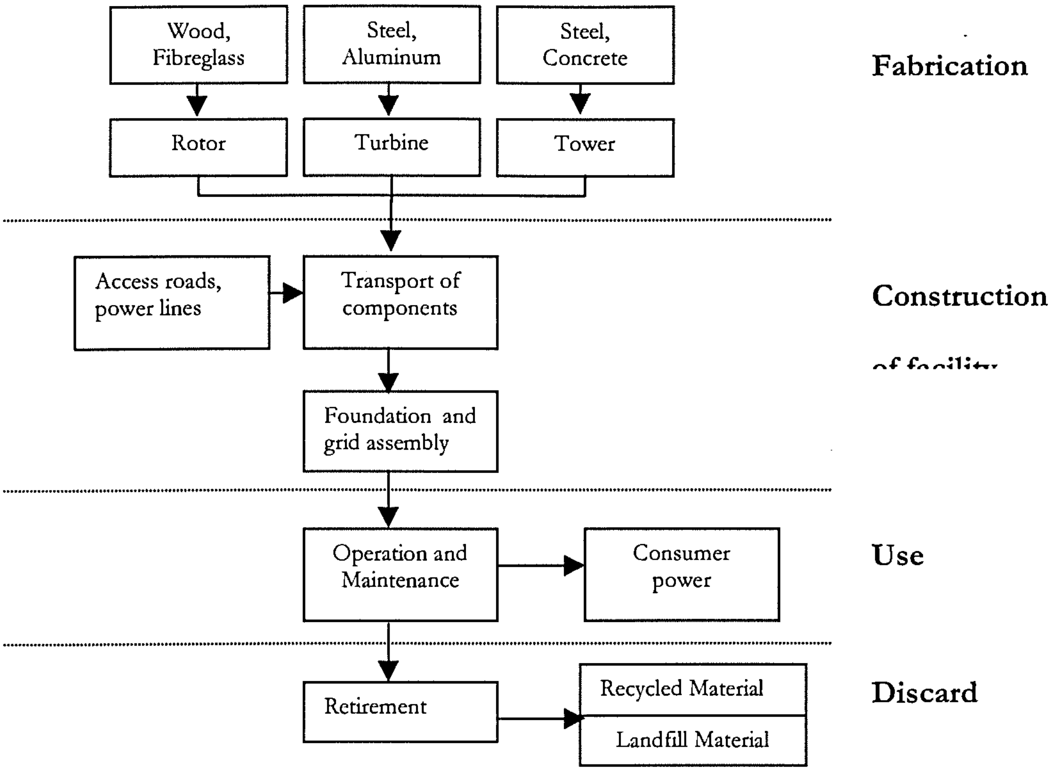

*Figure 12: Wind Turbine Process Model Using Block Flow Diagram*

## 4.3.6 CALCULATING POWER OUTPUT FROM WIND TURBINES

Wind turbines' power output is derived from local wind resources. Below, the general expressions for calculating wind energy output from a plant are shown. It should be noted that the power output in this case is related to the cube of wind speed. In a practical setting, proper siting of the plant has a pronounced effect on achieving optimal performance from the wind plant.

Design Variable: $A_w \equiv$ Windswept area of rotors ($m^2$)

Constants and derived variables: $\rho_w \equiv$ Air density ($kg/m^3$)
$\eta_w(t) \equiv$ Efficiency of wind turbine
Climatological variables: $v(t) \equiv$ Wind speed

Let $G_w(t)$ be the expression for the wind turbine power output. Thus, the calculation for wind generated power is,

$$G_w(t) = \tfrac{1}{2} A_w \cdot \rho_w \cdot \eta_w(t) \cdot v^3(t) \qquad (4.1)$$

Figure 13 (below) demonstrates the dynamics of a typical power generation curve from a wind turbine. As has been marked, most windmills have three characteristic windspeeds. The first is the *cut-in speed*, which defines the windspeed where the turbine will begin to output power. At the *rated windspeed* the windmill achieves maximum power output. The third major windspeed is the *maximum windspeed*, which is the maximum windspeed that the physical structure of the windmill can withstand.

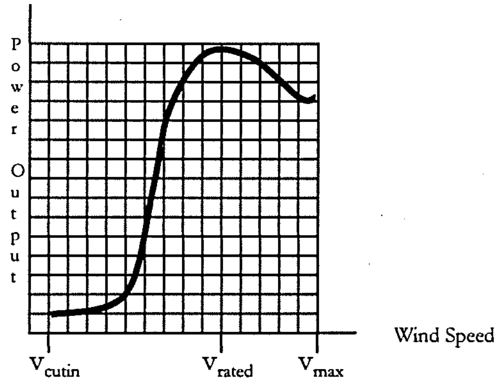

*Figure 13: A typical power curve for a wind turbine*

For simulation purposes, an alternative method to using the analytic expression for wind turbine power would be to use the manufacturer's power curve to calculate $G_w(t)$. This alternative approach may prove to be slower in computational terms, but it gains the realism of a time-varying efficiency and possibly simplifies complicated actual commercial turbine power output calculations.

## 4.4 SOLAR PHOTOVOLTAIC MATERIALS INVENTORY

The following sections (4.4.1-6) outline the modelling of the material inventory and power simulation for wind turbines. Sections 4.4.1-4 detail the process stages for wind turbines. Figure 14 in section 4.4.5 summarizes the process model that was outlined in the preceding sections. The results of the materials inventory as applied to the ASE 300-DG-50 [ASE, 1998] solar photovoltaic cell is summarized in Table 24, also in section 4.4.5. Finally, the power simulation for a wind turbine is shown in section 4.4.6.

### 4.4.1 FABRICATION OF SOLAR CELLS

Silicon cells are the most widely used and manufactured photovoltaic technology in North America. Other technologies such as cadmium telluride (CdTe), cadmium-iridium-selenide (CIS) and amorphous silicon (a-Si) cells are definitely candidates for future technologies. These experimental cells use some highly toxic and dangerous chemicals, in comparison to silicon cells. But, they have achieved significantly higher conversion efficiencies and use materials that are much lighter and easily manufactured. Production methods (especially for CIS) for these cell types have a greater potential to significantly lower the overall costs of deploying solar energy. The major disadvantage of these same technologies is the use of the highly toxic and hazardous material cadmium. As solar energy markets continue to grow the current dominant technology (silicon cells) will probably be usurped by one of the newer technologies due to the advances in power conversion efficiencies and cost. [Markvaart, 1993], [Bell, 1996], [Zweibel, 1990]

### 4.4.2 CONSTRUCTION OF SOLAR ARRAY

Assembly and construction of solar arrays is conducted similarly to other infrastructure projects. The bulk of materials that are used within this process consist of construction materials such as steel housings for the cell arrays and concrete foundations. In addition, energy is input in the form of transportation of the cells and raw materials.

### 4.4.3 USE

The operation and maintenance of a solar array involves a number of different activities. Over the lifetime of the solar array its back-up systems (such as batteries) must be replaced and serviced as needed. The useful lifetime of a solar cell is approximately 20 years. Batteries usually must be changed every 6 years, depending upon how heavily the system uses up the finite charge-discharge cycles of batteries (car batteries allow for 400 of such cycles). Back-up energy in solar arrays, especially in large deployments will probably not use batteries because of their cost, bulk and deleterious environmental effects when they leak. More likely will be that the solar arrays will be connected to an energy grid or for remote applications. Fuel cells will probably be the future storage medium of choice [Markvaart, 1993]. This report assumes that there is no battery or fuel-cell backup within the solar array. Thus, solar photovoltaic energy conversion becomes a fairly benign and passive process. But potential problems, especially with very large deployments would certainly be biosphere disruptions in migration patterns and habitat encroachment, which are yet to be fully understood.

### 4.4.4 DISCARD

The retirement of solar arrays involves a number of steps. The bulk of the concrete may be landfilled or possibly re-used as road paving material. The steel and aluminum in the cell frames and array housings can be almost completely recycled. But, care must be taken in disposing of the cells because they may potentially contain highly toxic substances such as cadmium or tellurium. The cells must be specially treated in order to extract the more dangerous chemicals from the cells. This requires special leaching facilities and containment facilities for eventually landfilling or diluting the harmful heavy metals.

## 4.4.5 INVENTORY AND PROCESS SUMMARY

Appendix A.2 contains the LCI template for the ASE 300-DG-50 solar photovoltaic cell. The materials inventory calculations for the ASE solar cell is presented in Appendix A.5. The materials summary is shown below in Table 24. Additionally, the process model is depicted in Figure 14.

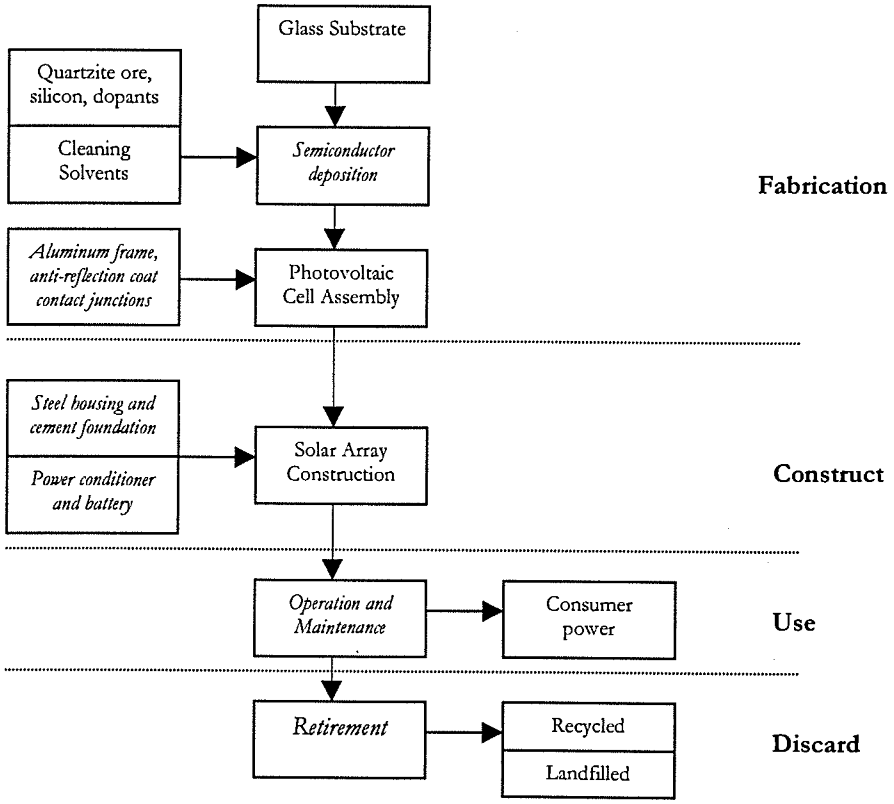

*Figure 14: Solar Photovoltaic Array Process Block Flow Diagram*

| **Item** | **Carbon Dioxide Emissions** |
|---|---|
| *Steel* | 126.9 kg $CO_2$/unit |
| *Glass* | 3.185 kg $CO_2$/unit |
| *Aluminum* | 37.1 kg $CO_2$/unit |
| *Cement* | 9.5 kg $CO_2$/unit |
| *Semiconductors* | 371.9 kg $CO_2$/unit |
| *Transport* | 0.35 kg $CO_2$/unit |
| ***Total Fixed CO2:*** | 548.9 kg $CO_2$/unit |
| ***Total Variable CO2:*** | 0 tonnes $CO_2$/unit |

*Table 24: Summary of ASE-300-DG/50 PV array $CO_2$ emissions*

## 4.4.6 CALCULATING POWER OUTPUT FROM SOLAR ARRAYS

Solar photovoltaics generate power by converting solar radiation into electricity. The analytic expression for power output is fairly simple. The power output is simply the total irradiation of the solar cell area times the efficiency times the area power density of the solar radiation on the surface of the cell. But, this is deceptively simple because the solar irradiation (insolation) is usually measured in two general components. The first is direct sunlight or solar irradiation that is the radiation incident on a surface perpendicular to the Sun's rays. The second component of the solar irradiation is the diffuse irradiation that is defined by the power density on a surface parallel to the sun's rays.

| | | | |
|---|---|---|---|
| Design variable: | $A_{pv}$ | ≡ | Area of photovoltaic cells ($m^2$) |
| Climatic variables: | $R(t)$ | ≡ | Direct and diffuse insolation ($kWh/m^2$) |
| | $Temp(t)$ | ≡ | Temperature (°C) |
| Parameter variables: | $\eta_{pv}(Temp, t)$ | ≡ | Efficiency of cells |

As shown above, the temperature of the cell affects their efficiency. For northern climates, the fluctuation of temperatures on diurnal, seasonal, and yearly periods are large enough to warrant the accounting of the change in efficiency.

Let $G_{pv}$ be the power output from a solar photovoltaic cell. The calculation for the output power would simply be [Markvaart, 1993],

$$G_{pv} = A_{pv} \cdot \eta_{pv}(Temp,t) \cdot R(t) \qquad (4.2)$$

Thus for a fixed solar array, as the Earth and Sun turn, the incident radiation on the cell will be only a part of either the diffuse or direct irradiation. In order to correct for this, the solar cells angle to the Sun's direct rays must be tracked and the solar irradiation values similarly corrected. Not all commercial solar arrays require these added computations because the solar arrays track the sun so that maximum energy conversion can be achieved.

## 4.5 LIQUEFACTION OF WOODY BIOMASS MATERIALS INVENTORY

The following sections (4.5.1-4) outline the modelling of the material inventory and power simulation for a biomass integrated gasifier gas turbine system (BIG/GT) which uses liquefaction for converting biomass to fuelstock. Sections 4.5.1-2 detail the process stages for BIG/GT fuel production. Section 4.5.3 summarizes the overall materials inventory for the BIG/GT system. Figure 15 in section 4.5.3 summarizes the process model that was outlined in the sections 4.5.1 and 4.5.2. The results of the materials inventory as applied to the biomass system in [Mann, 1996] is summarized in Table 26, also in section 4.5.3. Finally, the power simulation for a BIG/GT system is shown in section 45.4.

### 4.5.1 AGRICULTURE

For growing woody biomass, the general agricultural process is much the same as for other agricultural crops such as corn or wheat. The largest deviation from typical farm crops is that a stand of woody biomass is not harvested yearly. Rather, a plantation would be harvested along periods ranging from 3-10 years. This periodic harvest is highly dependent on the crop species. Aside from this, the cultivated woody crops will usually be given fertilizers and pesticides. Application of herbicides and weeding do not become common after the trees reach a certain age (usually at around the mid-point of the growth period between harvests). But, as mentioned, wood agriculture uses the same modern agricultural equipment, irrigation systems, fertilizers, and the need to transport the harvested biomass via train or roads as more common cropping systems. [Ledin, 1996a], [Sharpe, 1985]

Similarly, agricultural effects such as desertification, land-based discharges of chemicals into local biota and water systems from fertilizers and pesticides, and ecological disruption by usurping habitat or blocking migration routes are still possibilities in dedicated biomass agriculture. One of the possible highlights from widespread cultivation of trees is the potential for net sequestering of carbon from the atmosphere into the soil. This is not always the case, and is strongly a function of both the tree species and the local soil type. Dedicated woody biomass may be a means to reduce aggregate $CO_2$ emissions and at the same time meet future power demand. [Mann, 1996]

### 4.5.2 LIQUEFACTION

Liquefaction is the process of extracting liquid fuel from a feedstock. For woody biomass this usually involves the following steps:

1. Raw feedstock is made into wood chips
2. Chips are dried in a kiln
3. Dried wood chips are then bio-degraded and this gasification process produces the fuel

These steps in liquefaction are summarized below in Table 25. The table also details some of the hazardous environmental effects of these stages.

| Stage | **Harmful Effects** | **Use of contaminated waste** |
|---|---|---|
| Wood chipping | Air-borne particulate from saw dust | |
| Kiln drying | | Contaminants carried on saw dust through flue gas |
| Gasification | Ash, char and tar | Waste products may have excessively high heavy metal content |

*Table 25: Effects from the general stages of biomass liquefaction.*

### 4.5.3 SUMMARY OF MATERIALS FOR A BIOMASS INTEGRATED GASIFIER GAS TURBINE SYSTEM

There are many problems in attempting to generalize a biomass conversion system. The first problem is that candidate biomass feedstock can be from many different sources. Systems exist which utilize for feedstock municipal waste, waste wood from lumber, bagasse from sugar cane, and dedicated cropping of grasses, shrubs and trees. These methods of biomass feedstock procurement fall under two main categories; waste materials and dedicated cropping. One of the major problems with using waste products (especially municipal waste) is that the contaminants that are present in the waste materials (such as wood products from a pulp and paper mill) pass these contaminants into the power generation systems' effluence. And thus, the effluence from these systems can be highly polluting. Dedicated cropping or the use of only unadulterated waste material (such as wood chips from cutting timber or bagasse from sugar cane) are usually recommended [Cook, 1996], [Wright, 1992]. Within the realm of dedicated cropping of biomass feedstock, theoretically, almost any plant species can be used. Practically, local conditions and cost dictate which plants (either natural or engineered) would prove to be the most suitable for a particular application. Finally, the process for extracting fuel from the feedstock may highly differ between systems. Through different processes the resultant fuel may be gas ( e.g. methane), liquid ( e.g. ethanol) or solid (e.g. charcoal). The possible fuel types are dependent on the chemical and physical make up of the feedstock. Thus, gross generalization of biomass conversion systems is not possible. But, for the LCA one must attempt to specify the assumptions and system components that are present in the system under study. This study uses the values from [Mann, 1996] for the thermal plant (this is outlined in the following section) and the woody biomass chosen was willow cropping as presented in [Ledin, 1996b] with approximations for the agricultural inputs from a number of other sources; [Perlack, 1992], [Shapouri, 1995], [Hohenstein, 1994], [Cook, 1996]. The results of the life-cycle inventory from the various sources mentioned in the paragraph above, are summarized below in Table 26. Figure 15 summarizes the process model considered in this inventory for the biomass component.

| **Item** | **Carbon Dioxide Emissions** |
|---|---|
| *Steel* | 329.1 tonnes $CO_2$/plant |
| *Iron* | 3.8 tonnes $CO_2$/plant |
| *Aluminum* | 4.7 tonnes $CO_2$/plant |
| *Cement* | 210.1 tonnes $CO_2$/plant |
| *Transport* | 0.87 tonnes $CO_2$/plant |
| ***Total Fixed CO2:*** | 548.6 tonnes $CO_2$/unit |
| *Fertilizer* | 34.9 kg $CO_2$/ha-yr |
| *Fossil Fuel* | 0.35 kg $CO_2$/ha-yr |
| *Transport* | 14.9 kg $CO_2$/ha-yr |
| *Above-ground Carbon* | -4.3 Mg $CO_2$/ha-yr |
| *Soil Sequestered Carbon* | -5.5 Mg $CO_2$/ha-yr |
| *Electricity Generation* | 0.332 kg $CO_2$/kWh |
| ***Total Variable CO2:*** | 50.15 kg $CO_2$/ha-yr (Agriculture) |
|  | -5.5 Mg $CO_2$/ha-yr (Tree growth) |
|  | 0.332 kg $CO_2$/kWh (Power Gen.) |

*Table 26: Summary of dedicated woody biomass system $CO_2$ emissions*

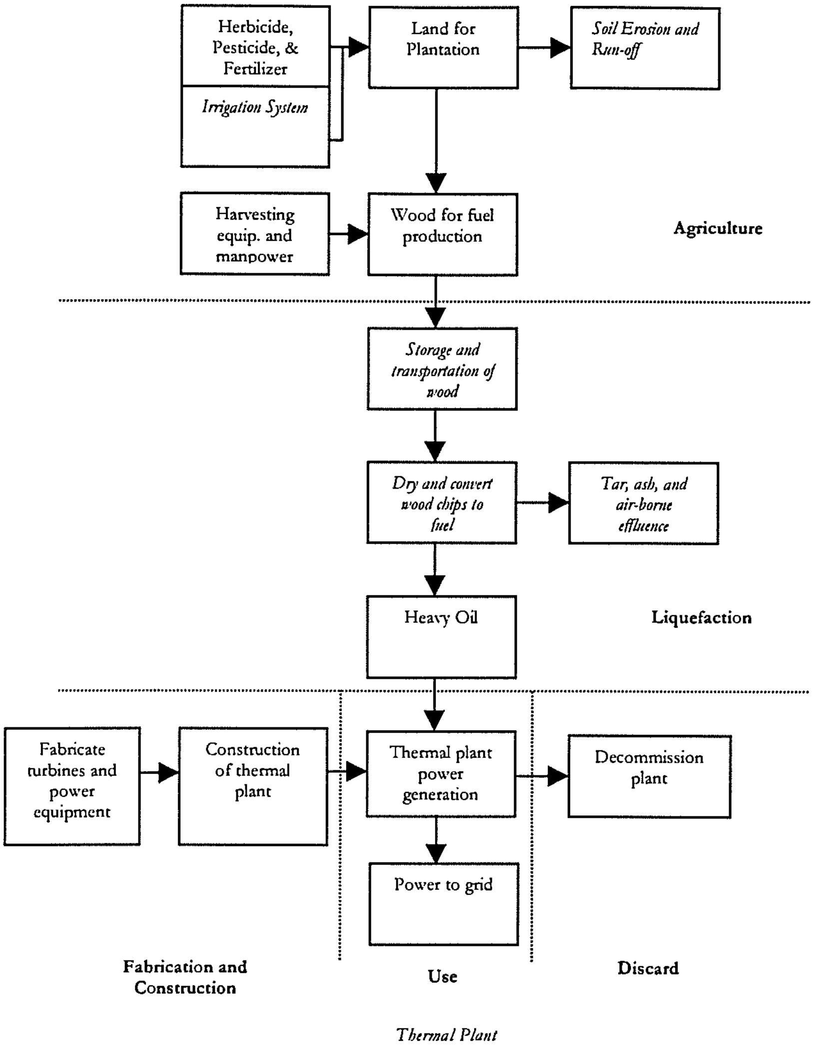

*Figure 15: BIG/GT Liquefaction Process Block Flow Diagram*

## 4.5.4 CALCULATING POWER OUTPUT FROM BIOMASS SYSTEMS

BIG/GT power system output can be modelled using an expression that in general has the form:

$k_t$ ≡ Percentage of maximum power output
$I_{th}$ ≡ Installed capacity

$P_{th}$ ≡ Power output of thermal plant = $k_t I_{th}$

The fuel consumption for such a plant is usually of the form:

$f_{idle}$ ≡ Fuel consumed by keeping generator idle (l/hr)
$f_p$ ≡ Fuel consumed by power generation (l/kWh)
$f_{th,t}$ ≡ Total fuel consumed in timestep t $= f_{idle} + k_t I_{th} f_p$

Biomass-based power generation must also take into account the logistics and availability of fuel. In cases where power cultivation is assumed to be regionally sustainable, a suitable model must be chosen which would be used to simulate the regional biomass yield, and the required area and facilities for supplying fuel to the plant.

## Calculating Harvest and Land Size Using a Biomass Growth Model

One of the additional components that was required by this system was a method for estimating the land area of the biomass power component. In Matlab, a continuous-time Markov (CTM) plant growth model based on [Sharpe, 1985] was implemented. This model was designed for a broad range of general floral types ( grasses, woody shrubs, small trees, and large trees) that would grow within a resource competitive environment. It modelled plant growth through a set of growth factors and plant growth states (notably, the processes of photorespiration, nutrients metabolism through cellular processes, and photosynthesis). The model simulated competition for growth factors such as nutrients (such as fertilizer), light and water through the setting of parameters which represented the percentage of the optimal growth factors that would be available to the plant. These were assumed idealized to 100% for the results in this study. The CTM model presented by Sharpe (1985) recognized the fact that temperature effects were not taken into account in the model. For Canadian climates this was problematic because of the short growing season. The CTM model did contain a parameter for the photorespiration rate for the plant species. This respiration rate was made temperature sensitive by using a very coarse linear approximation to a photorespiration curve from [Weier, 1982].

The plant species used in this study was the willow tree species Salix [Ledin, 1996b]. The maximal photorespiration rate was assumed to occur at 35 °C, with a decreasing rate of 15% per 5 °C below the temperature at the maximal rate to a minimum of 0.5%. Also, above the maximal rate temperature, the drop-off was markedly more steep at -45 % per 5 °C increase in temperature.

The CTM model was configured to use the parameterization for small tree growth in the mid-west United States. The growth model was then normalized to output the percentage of maximum tree size that had been achieved (as opposed to the actual tree size). From [Ledin, 1997], the maximum size for the above-ground growth for a willow plantation in Sweden was estimated at 200 tonnes per hectare. The harvest period for willow trees range from 4-7 years, so a harvest period (the time between successive harvests for a stand of coppiced trees) was chosen to be 5 years. A harvest was assumed to be idealized such that the plantation would be cut to the unfettered conditions of the plantation at 10% of the maximum size. So, it was assumed that the cutting would not disrupt the plant growth cycle beyond the loss in plant mass.

Figure 16 (below) shows the growth of Salix in Whitehorse, London and under optimal conditions. The graphs were generated with a starting stand of 1 tonne of biomass. The optimal curve shows growth with neglecting temperature effects on photorespiration and assuming ideal supply of nutrients, sunlight mad water. The graphs for Whitehorse and London show the effects of temperature on biomass growth (although the resources of light, nutrients and sunlight were still assumed to be ideal).

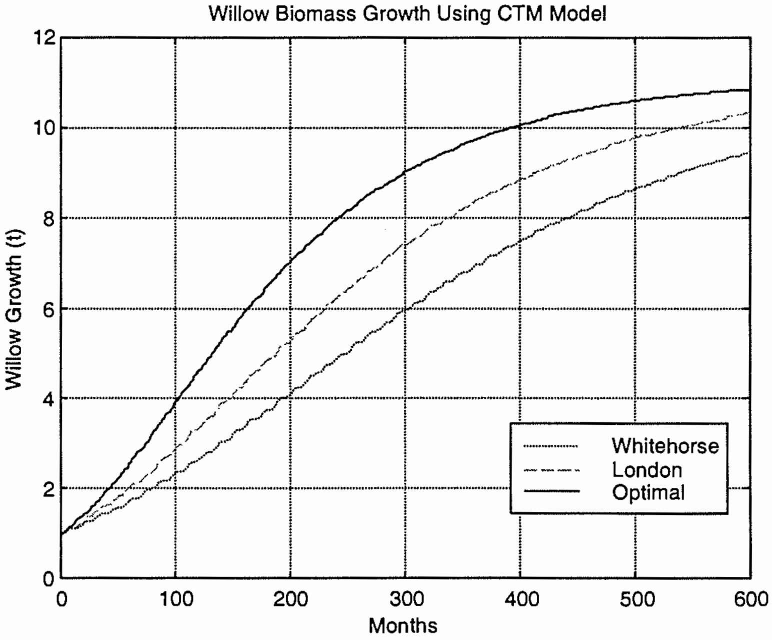

*Figure 16: Simulated growth of Salix using the CTM model*

From the CTM model, it was estimated that within five years a stand of willows in London, Ontario would reach to approximately 25% of their maximum size, whereas in Whitehorse, it was estimated that the trees would reach to approximately 20% of their maximum size. The power simulation assumes an existing infrastructure and this would include an established plantation. Thus, the initial conditions for the plots would be a stepped size starting from the regional 5-year size (25% and 20%, respectively) and ending the last plot to be at 10% (i.e. it had just been harvested).

## 4.4 SUMMARY

This chapter presented the rationale and summary values for an LCI of wind turbine, solar photovoltaics, and BIG/GT systems. Detailed calculations of the materials accounting for all of these systems has been included in Appendix A.

The next chapter uses these results to build an IRES simulation based on the REOS model. Additionally, the results for using this REOS model with goal-attainments to investigate the suitability of this type of energy system in two Canadian cities (London, Ont. and Whitehorse, Yukon) are presented.

# CHAPTER 5: EXAMINING ATTAINMENT OF GOALS WITHIN A RENEWABLE ENERGY SYSTEM

## 5.0 BACKGROUND

This chapter demonstrates the use of goal-programming in the LCA improvement stage. Goal-attainment algorithms are used to find feasible designs for IRES networks, such that the network will meet prescribed goals. Tradeoffs between goals can then be assessed by using the goal-attainment system to map out target regions between contending goals. As an example, one may examine the relationship between carbon dioxide emissions and the production price of electricity by exploring the feasibility of a range of emissions levels over a range of reasonable pricing levels. The product of this stage is a reasonable estimation of the network deployment and performance that would be required for the specified load.

The goal of this thesis was to demonstrate the methodological framework of the LCA as applied to IRES networks.

## 5.1 PRELIMINARY SET-UP

The following sections detail the sources and reasoning for the simulated load demand (5.1.1), long-term backup power source (5.1.2), climatic data (5.1.3), economic costing model (5.1.4), and finally, how sensitivity analysis (5.1.5) was conducted.

### 5.1.1 LOAD DEMAND

The basic load curve was taken from the Hybrid2 software package [Hybrid2, 1997]. The load curve was for a small installation in the 100 kW range. The load time-series was a single year of hourly data points. This load curve was linearly scaled by a factor of 100 and then made into a multi-year data series by assuming the load demand would be the same across multiple years. The unfactored load-curve is depicted below in Figure 17 for a period of 136 weeks. It is shown as a weekly maximum load, although the data was provided in hourly time steps.

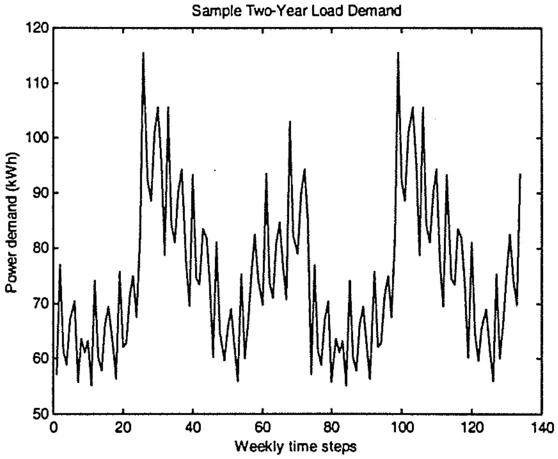

*Figure 17: Basic load curve used for both London and Whitehorse tests.*

## 5.1.2 LONG-TERM COAL-FIRED BACKUP

Coal-based electricity generation was chosen as the long-term backup for this study. Coal is one of the most polluting, but convenient electricity generation technologies. Coal is an abundant fuelstock and it is relatively cheap. It may be safely stored and transported. Worldwide, coal-fired power is the dominant electricity generation technology. Below in Figure 18, worldwide electricity generation by fuelstock is depicted [Johansson, 1993].

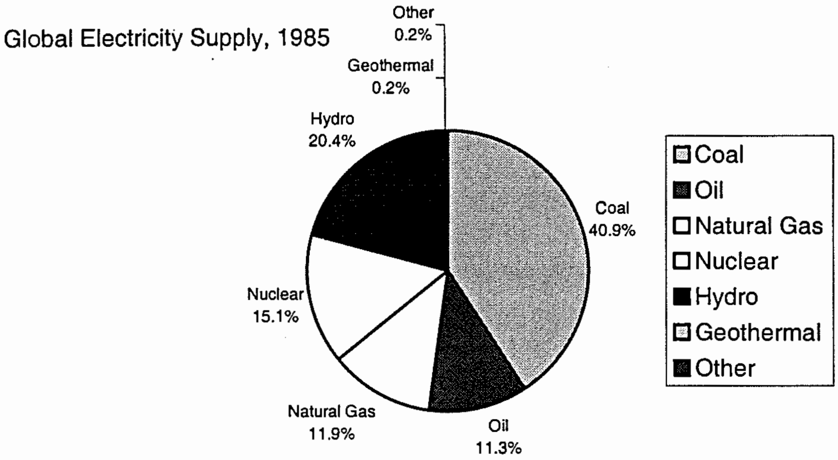

*Figure 18: Graph of worldwide electricity supply by fuelstock.*

Table 27 (below) summarizes the ranges of emissions and costs associated with coal generation.

| | |
|---|---|
| **Power generation prices** | \$0.05-0.10/kWh |
| **$CO_2$ Emissions** | 1-2 t CO2/kWh |
| **Land requirements** | Negligible primary land requirements, possibly secondary land requirements such as railway and road infrastructure, mining and processing operations |
| **Reliability** | Reliability based on adequate supply of fuel have yielded upwards of 99.99% reliability and availability |
| **Typical Plant Sizes** | >100 $MW_e$ |

*Table 27: Typical performance for coal powered electricity generation plants.*

### 5.1.3 BRIEF OVERVIEW OF STUDY SITES

London, Ontario, Canada is a large in-land urban centre with a population of approximately 300,000 people. It is centrally located in south-western Ontario, approximately mid-way between Lake Huron and Lake Ontario. London is situated within a fairly dense settlement of small-sized cities and extensive agricultural lands. Mann(1996) estimates that in highly populated regions land availability is usually on the order of 10% within a given area. Thus, if a particular installation requires 10000 ha of land, in urbanized regions, the installation will probably be dispersed over an area of 100000 ha. Below, the climatic conditions for London are shown (Table 28).

| | |
|---|---|
| Wind speed | Annual mean speed at ground-level 4.1 m/s |
| Insolation | Annual mean daily direct insolation 0.162 kW/m2 |
| Temperature | Annual mean temperature 7.1 °C |
| Location | Latitude 43.5° N , Longitude 81° W |

*Table 28: London, Ontario climate and location*

| | |
|---|---|
| *Wind speed* | Annual mean speed at ground-level 3.6 m/s |
| *Insolation* | Annual mean direct insolation 0.133 kW/m2 |
| *Temperature* | Annual mean temperature 0 °C |
| *Location* | Latitude 61° N, Longitude 135° W |

*Table 29: Whitehorse, Yukon climate and location*

In contrast, Whitehorse, Yukon, Canada is a small very northern settlement of approximately 15000 people. It has a very harsh winter climate, with large swaths of tundra in the general area. The region is sparsely populated. The major industries in the far north communities are mineral and oil exploration operations. Above, the climatic conditions for Whitehorse are shown above in Table 29.

### 5.1.4 COST CRITERIA

This section presents the various costing models that were employed in this system. Specifically, the costing formulations for $CO_2$ emissions, monetary costs, and land requirements for an IRES are discussed.

The nomenclature that is used to represent the system costs are as follows:

| **Symbol** | **Represents** |
|---|---|
| $c,e,h$ | Unit economic cost, $CO_2$ emissions, and land area |
| $C,E,H$ | Total economic cost, $CO_2$ emissions, and land area |
| $L$ | Lifetime of facility |
| $T$ | Length of time of simulation |
| $U$ | Total simulation unserved load demand in kWh |
| $X$ | Design variables (see below in Table 31) |

*Table 30:Nomenclature for representing costs of REOS LCA model*

The design variables that were used in the study were:

| **Technology** | **Symbol** | **Units** |
|---|---|---|
| Solar Photovoltaic | $x_{pv}$ | $m^2$ of installed solar cell area |
| Wind Turbine | $x_{wind}$ | $m^2$ of installed windswept rotor area |
| Thermal Plant | $x_{thermal}$ | Peak power ($kW_p$) of installed thermal capacity |

*Table 31:Design variables for simulation*

### Incorporating a Cost Vector into Goal-Attainment

In this study, four performance, or cost, functions were considered. These were the production price of energy ($/kWh), regional land occupation (hectares of land), air-borne carbon dioxide emissions (kg $CO_2$/kWh) and the load demand that remained unserved (% of total load). For goal-attainment, as presented in equation 3.1, the cost $C$ and target $G$ were replaced with vector values as shown below.

### Facility Lifetimes

For the three facility types (photovoltaics, wind turbines, and thermal plant) the lifetimes are taken from the LCI in chapter 5. Assuming a continuous single-species crop rotation, biomass plantations for willow trees has been estimated to be approximately 20 years, which is the amount of time before the land is no longer suitable for willow agriculture [Ledin, 1996b]. After this period, the land should be left fallow for a time.

The lifetimes assumed for the various system components were:

| Component | Symbol | Years |
|---|---|---|
| Solar Photovoltaic | $l_{pv}$ | 15 |
| Wind Turbine | $l_{wind}$ | 20 |
| Thermal Plant | $l_{thermal}$ | 30 |
| Plantation | $l_{biomass}$ | 20 |

*Table 32: Assumed lifetimes of system components*

## Economic Costs

The costs for photovoltaics, wind turbines, and biomass agriculture includes the costs of land acquisition. This was assumed to be $10000/ha in both Whitehorse and London. This land price was chosen because generic pricing was highly problematic to generalize. It is assumed that this price was a maximal price in both of the test sites. The unserved load demand cost was the unit price of coal-based electricity (which acts as the long-term backup energy source for this study) as estimated in [Berrie, 1993].

| **Economic Cost** | **\$US** | **Symbol** | **Units** | **Source** |
|---|---|---|---|---|
| Solar Photovoltaic | \$40 | $c_{pv}$ | \$/m$_2$ of installed solar array area | [Hybrid2,1997] |
| Wind Turbine | \$65 | $c_{wind}$ | \$/m$_2$ of installed windswept area | [Hybrid2,1997] |
| Biomass Agriculture | \$20 | $c_{biomass}$ | \$/(ha-yr) of farmland | [Mann,1996] |
| Fuel Processing | \$0.50 | $c_{fuel}$ | \$/litre bio-fuel produced | [Mann,1996] |
| Thermal Plant | \$30 | $c_{thermal}$ | \$/kW$_p$ of installed capacity | *[Mann,1996]* |
| Unserved load demand | \$0.05 | $c_{ue}$ | \$/kWh of unserved demand | [Berrie, 1993] |

*Table 33: Economic unit cost summary*

The following equations show how the total costs for the system were calculated. For the facility costs (solar PV arrays, wind turbines, and thermal plant), the installed capacities were multiplied by the unit costs and the proportion of the simulation period of the facility lifetime.

$$C_{pv} = c_{pv} \cdot x_{pv} \cdot \frac{T}{l_{pv}} \qquad (5.1.4.1a)$$

$$C_{wind} = c_{wind} \cdot x_{wind} \cdot \frac{T}{l_{wind}} \qquad (5.1.4.1b)$$

$$C_{thermal} = c_{thermal} \cdot x_{thermal} \cdot \frac{T}{l_{thermal}} \qquad (5.1.4.1c)$$

For the biomass plantation, the costs of agriculture and fuel production were calculated. The area of the plantation was derived from the CTM biomass growth model (Section 4.5.3), which provided the land estimate. The fuel production $F_i$ per period $i$ used the energy content in the harvested biomass and divided this by the energy content of heavy fuel oil given in [BUWAL, 1993].

$$C_{biomass} = c_{biomass} \cdot A_{plantation} + \sum_{i=0}^{T} c_{fuel} \cdot F_i \qquad (5.1.4.1d)$$

The unserved load demand cost was simply the total unserved demand over the period of simulation multiplied by the appropriate unit cost.

$$C_{ue} = c_{ue} \cdot U \qquad (5.1.4.1e)$$

### $CO_2$ Emissions

The $CO_2$ emissions in Table 34 were taken from the results of the LCI presented in Chapter 4.

| $CO_2$ Cost | kg $CO_2$ | Symbol | Units |
|---|---|---|---|
| Solar Photovoltaic | $2.22 \times 10^5$ | $e_{pv}$ | kg $CO_2/m_2$ of installed solar array area |
| Wind Turbine | $1.23 \times 10^5$ | $e_{wind}$ | kg $CO_2/m_2$ of installed windswept area |
| Biomass Agriculture | $-5.5 \times 10^3$ | $e_{biomass}$ | kg $CO_2$/(ha-yr) of farmland |
| Above-ground Sequestration | $-4.3 \times 10^3$ | $e_{ag}$ | kg $CO_2$/(ha-yr) of farmland |
| Bio-Fuel Combustion | $1.1 \times 10^{-4}$ | $e_{fuel}$ | kg $CO_2/kW_p$-hr |
| Thermal Plant | $549 \times 10^3$ | $e_{thermal}$ | kg $CO_2/kW_p$ plant |
| Thermal Plant Idle | 1 | $e_{idle}$ | kg $CO_2$/hour |
| Unserved Load Demand | 1027 | $e_{ue}$ | kg $CO_2$/kWh of coal-based power |

*Table 34: $CO_2$ emission unit costs*

It should be noted that the biomass agriculture includes life-cycle emissions from fertilizer, machinery and soil sequestration. $CO_2$ sequestration from biomass growth should have been calculated via the CTM model. But, the CTM model was calibrated to only calculate the above-ground growth. So, mean values of growth from the literature reviews were used for both below-ground and above-ground sequestration instead. Soil sequestration was taken from [Cook, 1996] and above-ground foliage was estimated from [Ledin, 1997] and [Ledin, 1996b].

The thermal plant requires a certain amount of fuel to keep it running whether it is producing electricity or not. The calculation for plant idling was derived from [Hybrid2, 1997] by scaling the emissions from a 100 kW$_p$ gas turbine. This was done on the assumption that the scaling of gas turbines are linear in their scaling of power capacities, because the idling cost was not made explicit in [Mann, 1996].

The following equations show how the total CO$_2$ emissions were calculated. The emissions were calculated based on the total proportions of emissions over the period of the simulation.

The calculations for emissions from solar photovoltaics and wind turbines is similar to those as for economic costs (Equations 5.1.4.1a and 5.1.4.1b)

$$E_{pv} = e_{pv} \cdot x_{pv} \cdot \frac{T}{l_{pv}} \qquad (5.1.4.2a)$$

$$E_{wind} = e_{wind} \cdot x_{wind} \cdot \frac{T}{l_{wind}} \qquad (5.1.4.2b)$$

The thermal plant emissions stemmed from three sources; (i) plant facility construction, (ii) power generation, and (iii) power plant idling. $T_{hermal}$ refers to the total power generated over the period of the simulation by the thermal plant. It was assumed that the idling emissions were present for all time steps.

$$E_{thermal} = e_{thermal} \cdot x_{thermal} \cdot \frac{T}{l_{thermal}} + P_{thermal} \cdot e_{fuel} + T \cdot e_{idle} \qquad (5.1.4.2c)$$

The biomass plantation was calculated from the above-ground growth carbon content and soil sequestration rate.

$$E_{biomass} = \left(e_{ag} + e_{biomass}\right) \cdot A_{biomass} \cdot T \qquad (5.1.4.2d)$$

The unserved load demand $CO_2$ emissions were calculated from the total unserved load demand multiplied by the emissions due to coal-based power.

$$E_{ue} = e_{ue} \cdot U \qquad (5.1.4.2e)$$

**Land Occupation**

The land unit costs were as follows:

| **Technology** | Area (ha) | **Symbol** | **Units** |
|---|---|---|---|
| Solar Photovoltaic | $1 \times 10^{-4}$ | $h_{pv}$ | ha/m$^2$ of installed cell area |
| Wind Turbine | $25 \times 10^{-4}$ | $h_{wind}$ | ha/m$^2$ of windswept rotor area |

*Table 35: Land unit costs summary*

Solar photovoltaics is assumed to use only the cell area as the land occupation. The wind turbine was estimated to use a spacing of 5 rotor diameters. This was the minimum recommended spacing from [Johansson, 1993], which recommended a spacing of between 5 to 10 rotor diameters.

The following equations show how total land area was calculated for solar photovoltaics and wind turbine installations.

$$H_{pv} = h_{pv} \cdot x_{pv} \qquad (5.1.4.3a)$$

$$H_{wind} = h_{wind} \cdot x_{wind} \qquad (5.1.4.3b)$$

In Mann(1996), the load factor for a thermal plant was assumed to be 0.8. So, for a 100 $MW_p$ installation, it was assumed that the power plant would on average service a load of 80 MW. This assumption was maintained in this study for the land calculations for verification and simplicity. Thus, in order to estimate the amount of land needed for a biomass plantation, the mean annual energy harvest ($b_{avg}$ kWh/(ha-yr) ) across the five years of growth/harvest was used to meet a planned for annual power demand of 0.8 of the installed thermal capacity, $x_{thermal}$. The total power that would need to served would be 0.8 of the installed capacity multiplied by the number of hours in a single year. The total land needed for the year would be the total power divided by $b_{avg}$. The total estimated land required by the plantation would then be the single year size multiplied by 5, assuming that each year the same size of plantation was harvested. This is summarized below in Equation 5.1.4.3c.

$$H_{thermal} = \frac{0.8 \cdot x_{thermal} \cdot (365 \cdot 24) \cdot 5}{b_{avg}} \qquad (5.1.4.3c)$$

## 5.1.5 SENSITIVITY ANALYSIS

Sensitivity analysis was conducted using a finite-difference approximation of the gradients of the costs, $\overline{c}$, versus installed capacity, $\overline{x}$. In a set of results, such as shown in sections 5.3.2 and 5.4.2, the partial derivatives were calculated and then summed. It was assumed that the sensitive cost variables would then be identified by their corresponding coefficient's magnitudes.

Let $c(\overline{x})$ be the performance vector that represents the recognized costs in the system; namely price ($p$), $CO_2$ emissions ($CO_2$), land ($l$) and unserved energy ($ue$). Let $\overline{g}$ be the desired goals for the goal-attainment. Then, goal-attainment can be executed by running the constrained optimization,

$$c(\overline{x}) = \begin{bmatrix} c_p(\overline{x}) \\ c_{CO_2}(\overline{x}) \\ c_l(\overline{x}) \\ c_{ue}(\overline{x}) \end{bmatrix} \qquad \overline{g} = \begin{bmatrix} g_p \\ g_{CO_2} \\ g_l \\ g_{ue} \end{bmatrix}$$

$$\min f(\overline{x}) = c(\overline{x}) - \overline{g}, f(\overline{x}) \leq 0 \qquad (5.1.5.1)$$

The gradient function for $f(\overline{x})$ would thus be,

$$\nabla f(\overline{x}) = \begin{bmatrix} \frac{\partial c_p}{\partial x_{pv}} & \frac{\partial c_p}{\partial x_w} & \frac{\partial c_p}{\partial x_b} \\ \frac{\partial c_{CO_2}}{\partial x_{pv}} & \frac{\partial c_{CO_2}}{\partial x_w} & \frac{\partial c_{CO_2}}{\partial x_b} \\ \frac{\partial c_l}{\partial x_{pv}} & \frac{\partial c_l}{\partial x_w} & \frac{\partial c_l}{\partial x_b} \\ \frac{\partial c_{ue}}{\partial x_{pv}} & \frac{\partial c_{ue}}{\partial x_w} & \frac{\partial c_{ue}}{\partial x_b} \end{bmatrix} \qquad (5.1.5.2)$$

Let a solution from the goal-attainment be $x^*$. Then, finite-differencing at some small distance $\varepsilon$ from point $x^*$ could be used to numerically approximate the gradient in Equation 5.1.5.2.

For a single goal-attained point, the gradient's partial derivative terms would indicate a sensitivity based on the relative size of the terms. Let this approximated gradient matrix be F as shown in Equation 5.1.5.3.

$$\nabla f\big|_{x^*} = F = \begin{bmatrix} f_{p,pv} & f_{p,w} & f_{p,b} \\ f_{co_2,pv} & f_{co_2,w} & f_{co_2,b} \\ f_{l,pv} & f_{l,w} & f_{l,b} \\ f_{ue,pv} & f_{ue,w} & f_{ue,b} \end{bmatrix} \qquad (5.1.5.3)$$

In order to ascertain the sensitive parameters within a set of *n* goal-attained points, *F* would need to be calculated for each goal-attained point. This would produce a set of *n* matrices. This set of *F*-matrices could be represented as $\{F_1, F_2, \ldots, F_n\}$. One means of quick sensitivity analysis within this set would be to aggregate the *F*-matrices, and to examine the resultant matrix terms for their relative sizes (much the same as the analysis would be done with a single *F*-matrice). Equation 5.1.5.4 shows the calculation of this aggregated sensitivity matrix, which was termed as $S_n$. The absolute value of the *F*-matrices shown in Equation 5.1.5.4 means to take the absolute value of the individual *F*-matrix terms (as opposed to the determinant of *F*), so that negative terms would not cancel out positive terms.

$$S_N = \sum_{k=1}^{n} |F_k| \qquad (5.1.5.4)$$

It is noted that this method of sensitivity is not very accurate, reliable or rigorous, but was pursued due to the time constraints that were present in this study.

## 5.2 EFFECT OF COST OF ELECTRICITY PRODUCTION ON $CO_2$ EMISSIONS

The purpose of this section was to investigate the relationship between life-cycle air-borne $CO_2$ emissions levels and the unit price of electricity for IRES installations in London and Whitehorse.

### 5.2.1 METHOD

The bounds of target price were determined by using a baseline cost of $0.05/kWh, which was the assumed minimum cost of coal-fired power, and varying it to $0.15/kWh. Similarly, carbon dioxide emissions were varied from 0 to 1000 kg $CO_2$/kWh (from the inventory calculations in Appendix A, coal power produced 1027 kg $CO_2$/kWh). The test points that were used are pictured below (and demarcated by dots) in Figure 19.

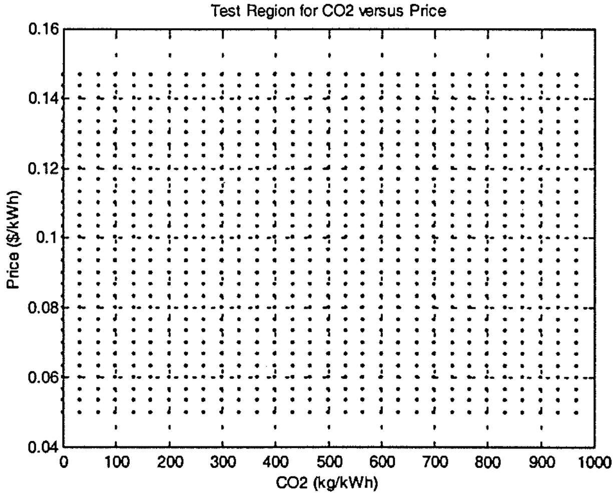

*Figure 19:* *Test points for testing the price of power and $CO_2$ emissions.*

## 5.2.2 OBSERVATIONS

Below the results of the test runs for $CO_2$ emissions versus price are presented in Figure 21 and Figure 22 for London and Whitehorse, respectively. The graphs show the resulting maps, with dots, where there were returned feasible installations. The infeasible regions were marked by the triangles in the graphs. One may note that the infeasible regions occur for the tests that were at the combined lowest cost and lowest $CO_2$ emissions.

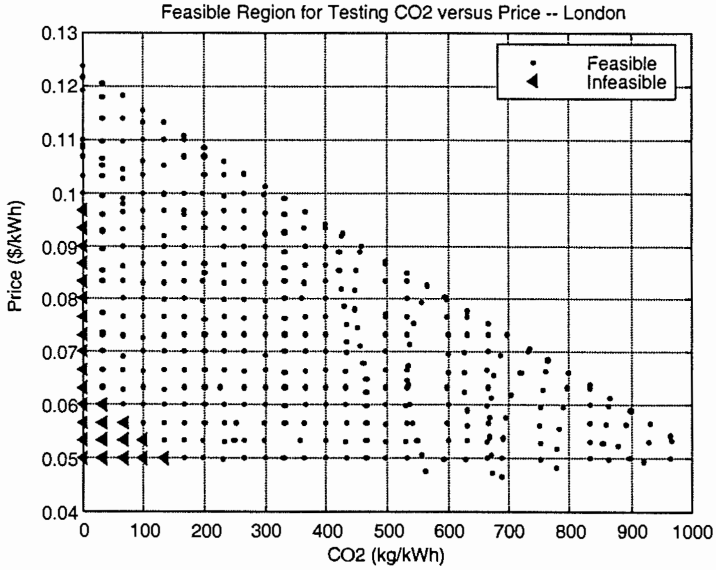

*Figure 20.:* *Results for London using the test points in Figure 19.*

The graph for London (Figure 20) shows that zero emissions is only feasible with a price of \$0.10-0.124/kWh for power. The best price to emissions tradeoff occurs at approximately an emission level of 160 kg/kWh, which would have a price between \$0.05-0.111/kWh.

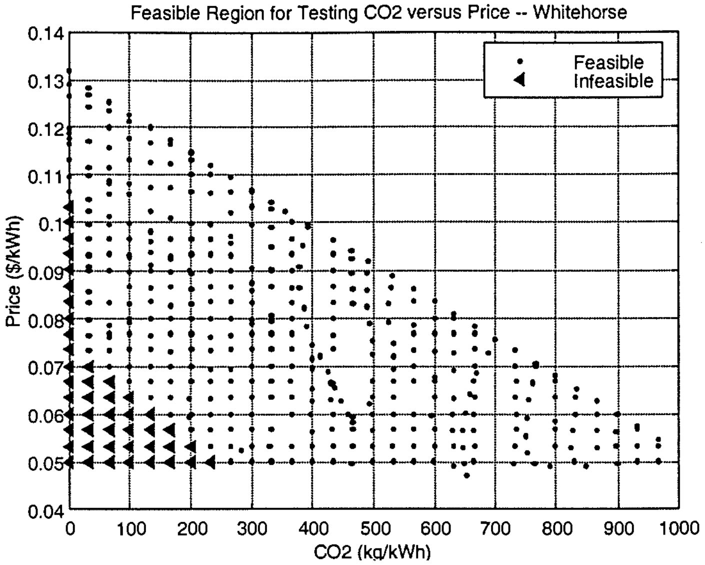

*Figure 21:* *Results for Whitehorse using the test points in Figure 19.*

The graph for Whitehorse (Figure 21) shows that zero emissions is only feasible with a price of $0.106-0.132/kWh for power. The best price to emissions tradeoff occurs at approximately an emission level of 240 kg/kWh, which would have a price between $0.05-0.111/kWh.

The following plots (Figures Figure 22, Figure 23, Figure 24, and Figure 25) show the relationships that resulted between price, $CO_2$ emissions and unserved demand. In this test, the goal-attainment was used to find designs based on varying $CO_2$ and price levels. Land was left as unconstrained. So, given adequate land resources, these plots suggest that substantial gains in $CO_2$ emissions over coal-generation can be gained through the use of RES technologies without unduly raising power prices.

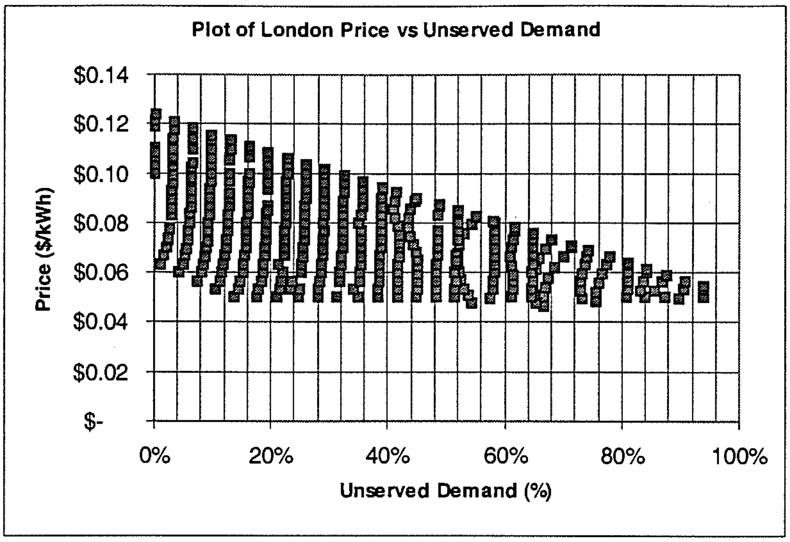

*Figure 22: Price versus unserved demand for London for price vs.$CO_2$*

In Figure 22, at 0% unserved demand the price of power ranges from $0.10-0.125/kWh for London. By relaxing the need for 0% unserved demand, prices can be brought to the $0.05/kWh level at 12-16% unserved demand.

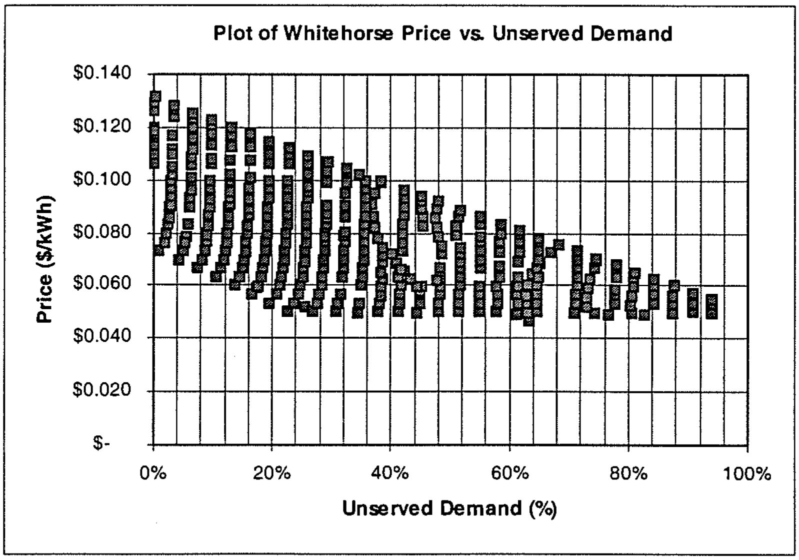

*Figure 23: Price versus unserved demand for Whitehorse for price vs.$CO_2$*

Similarly, for Whitehorse (Figure 23) , at 0% unserved demand the price of power ranges from $0.071-$0.132/kWh for London. By relaxing the need for 0% unserved demand, prices can be brought to the $0.05/kWh level at 20-24% unserved demand.

Below, the relationships between unserved demand and $CO_2$ emissions are depicted in Figure 24 and Figure 25, for London and Whitehorse, respectively. Using the unserved demand of 12-16% for London and 20-24% for Whitehorse, these graphs indicate that $CO_2$ emissions would be at 160-180 kg/kWh for London (Figure 24) and 220-240 kg/kWh (Figure 25) for Whitehorse. The projected prices at these unserved demand levels would be $0.05-0.111/kWh for London and $0.05-0.11/kWh for Whitehorse.

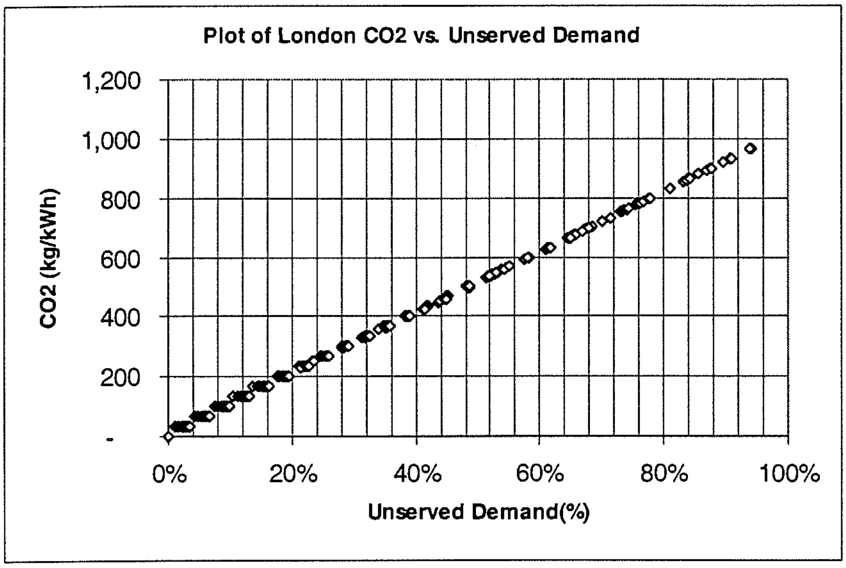

*Figure 24: $CO_2$ vs. unserved demand for London for price vs. $CO_2$ test*

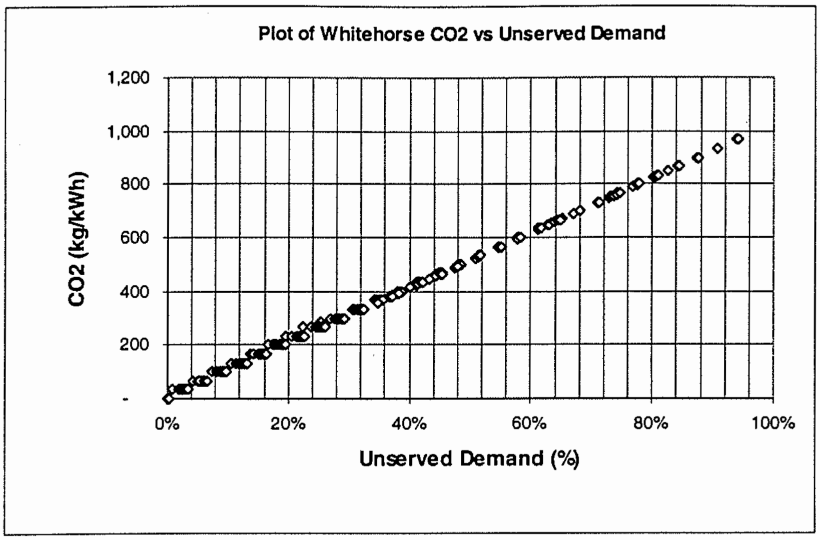

*Figure 25:* *$CO_2$ vs. unserved demand for Whitehorse for price vs. $CO_2$ test*

## Computation

There were 900 target points used in generating the results for both London and Whitehorse. Each target point required multiple REOS simulation runs which was driven by the goal-attainment algorithm. On a Pentium 300, with 96 Mb RAM running Windows NT Server 4.0, the total running time was approximately 2 hours per city for the 900 test points. Table 36 (below) summarizes the total REOS iterations run. For any single target, the goal-attainment was limited to a maximum of 80 runs for finding a feasible design (in cases where more than 80 runs were required it was assumed that the target point was infeasible).

| | **London** | **Whitehorse** |
|---|---|---|
| *Total Iterations* | 22872 | 24014 |
| *Number of Test Points* | 900 | 900 |
| *Feasible Designs Found* | 875 | 855 |
| *Infeasible Points Tested* | 25 | 45 |
| *Maximum Iterations For a Run* | 80 | 78 |
| *Minimum Iterations For a Run* | 16 | 16 |

*Table 36: Iterations of simulation required for price vs. $CO_2$ tests*

## Summary of Designs

The following tables give an indication of the power deployment that resulted from the runs of price versus $CO_2$ emissions. The total install is the installed capacity of the entire IRES system (i.e. deployments of wind, solar and biomass). The technology mix is also shown. These average values were calculated from the designs that resulted from the goal-attained regions presented in this section.

| ***London*** | **Total Install ($kW_p$)** | **%Solar** | **% Wind** | **% Biomass** |
|---|---|---|---|---|
| *Average* | 7,087 | 1% | 22% | 76% |

*Table 37: Average IRES install mix for London for price versus $CO_2$ test*

| ***Whitehorse*** | **Total Install ($kW_p$)** | **% Solar** | **% Wind** | **% Biomass** |
|---|---|---|---|---|
| *Average* | 8,103 | 1% | 25% | 73% |

*Table 38: Average IRES install mix for Whitehorse for price versus $CO_2$ test*

Overall, the designs that resulted from the goal-attainment were composed of predominantly wind turbine and biomass installed capacities.

### 5.2.3 SENSITIVITY ANALYSIS

The tables below show the sensitivity matrices for both Whitehorse and London (Tables 37 and 38, respectively). The dominant factors in the sensitivity analysis were the $CO_2$ emissions for solar photovoltaics and biomass gasification technologies. Land and unserved demand were not used in the goal-attainment algorithm and were left unconstrained (so, the results were insensitive to land and unserved demand).

| | **Price** | **$CO_2$** | **Land** | **Unserved Demand** |
|---|---|---|---|---|
| **Solar** | 0.117 | 220.1 | 0 | 0 |
| **Wind** | 0.578 | 162.5 | 0 | 0 |
| **BIG/GT** | 0.566 | 234.1 | 0 | 0 |

*Table 39: Sensitivity matrix ($S_{ij}$) for price vs. $CO_2$ tests for Whitehorse*

| | **Price** | **$CO_2$** | **Land** | **Unserved Demand** |
|---|---|---|---|---|
| **Solar** | 0.153 | 253.9 | 0 | 0 |
| **Wind** | 0.551 | 187.4 | 0 | 0 |
| **BIG/GT** | 0.586 | 253.2 | 0 | 0 |

*Table 40: Sensitivity matrix ($S_{ij}$) for price vs. $CO_2$ tests for London*

### 5.2.4 SUMMARY

The graphs of the feasible regions for both London and Whitehorse (Figure 19 and Figure 20) suggest that a zero $CO_2$ emissions level for the load demand is only feasible where prices for electricity are between \$0.10-0.124/kWh for London and \$0.106-0.132/kWh for Whitehorse.

But, substantial carbon gains over coal may be achieved without adding substantially to the per unit price of electricity from coal. Assuming that there is available and suitable land, designing for the emissions ranges of 100-200 kg/kWh for London, and 200-300 kg/kWh range for Whitehorse, the graphs (Figure 19 and Figure 20) show that maximally the price will be about $0.11/kWh, although it could also be as low as the assumed price of coal-power ($0.05/kWh). Additionally, from Table 37 (London) and Table 38 (Whitehorse), it becomes apparent that these tradeoffs in performance stem mainly from the deployment of biomass and wind technologies. Thus, for modest levels of $CO_2$ emissions, this would result in an overall electricity regime of approximately (as measured by percent of load serviced by either coal or solar-based renewables):

| | London | Whitehorse |
|---|---|---|
| Renewable | 84-88% | 78-80% |
| Long-term Backup (Coal) | 12-16% | 20-22% |

*Table 41: Electricity regimes for modest levels of $CO_2$ emissions*

## 5.3 EFFECTS OF CONSTRAINED LAND ON $CO_2$ EMISSIONS

The purpose of this section was to investigate the relationship between limited land availability and air-borne $CO_2$ emissions for IRES installations in London and Whitehorse.

### 5.3.1 METHOD

It was known that biomass systems took up the largest area of the technologies considered in this study, so its estimation was used to determine the test limits. From Mann (1996), a 100 MW thermal plant run at an average load factor of 0.8 that used the gasification and dedicated cropping of Douglas fir trees, used an estimated area of 44000 ha. The simulated load demand used was on the order of 10 $MW_p$. So, the target land area for these tests was chosen to be between 1000 and 11000 ha, or approximately double the estimated maximum land area from [Mann, 1996].

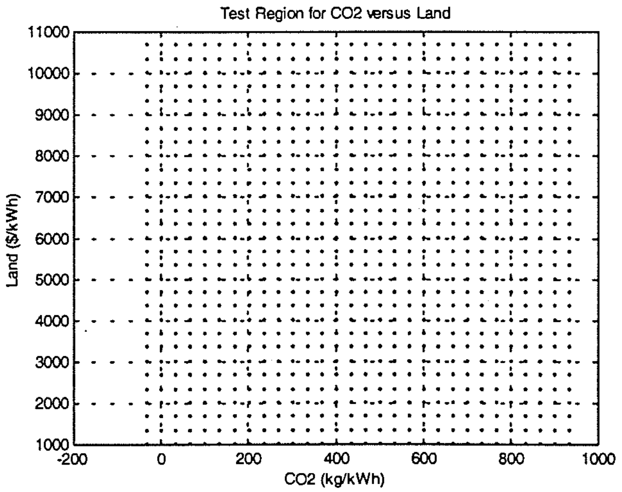

*Figure 26: Test points for testing limited land area and overall $CO_2$ emissions.*

Carbon dioxide emissions were varied from 0 to 1000 kg $CO_2$/kWh to coincide with the range of zero emissions to coal-fired power emissions (from the inventory calculations in Appendix A, coal power produced 1027 kg $CO_2$/kWh). The test points that were used are pictured (demarcated via dots) above in Figure 26.

## 5.3.2 OBSERVATIONS

Below, the results of the test runs for $CO_2$ emissions versus land area are presented in Figure 27 and Figure 28, for London and Whitehorse, respectively.

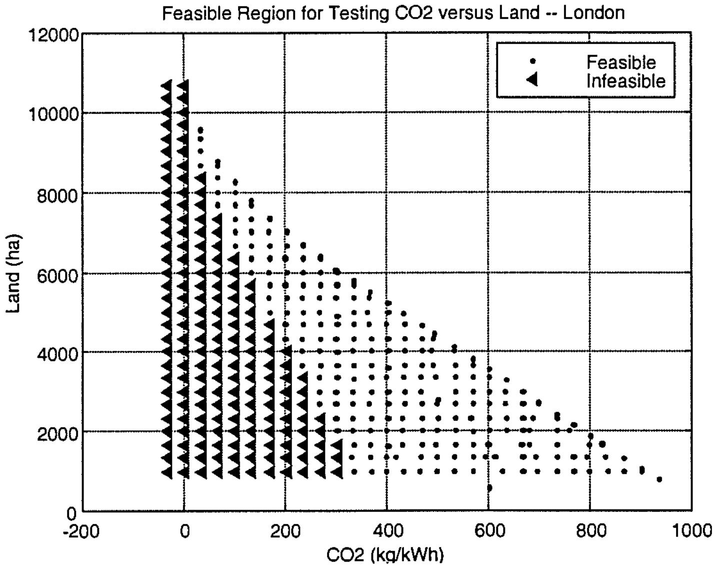

*Figure 27:* *Results for London using the test points in Figure 26.*

Figure 27 shows that zero emissions is not feasible for London within the land areas tested. The best land area to $CO_2$ tradeoff is at an emission level of 320 kg/kWh. At this emission level, the land area ranges from 1000-5900 ha.

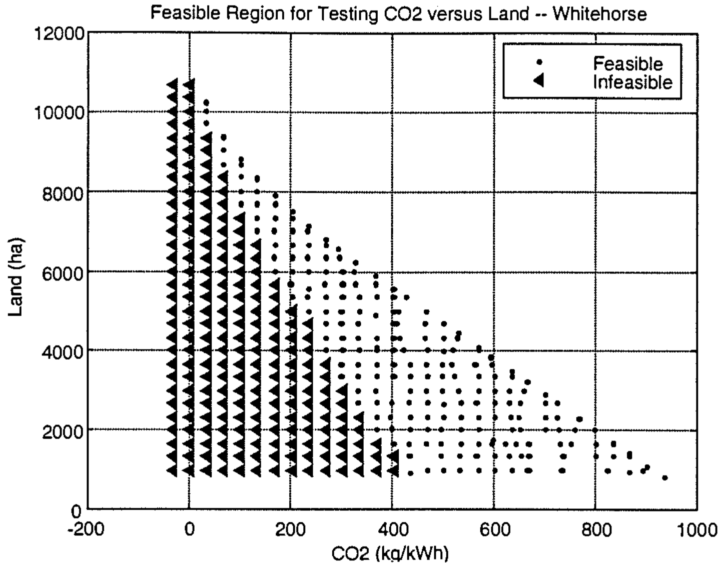

*Figure 28:* *Results for Whitehorse using the test points in Figure 26.*

Figure 28 shows that zero emissions is not feasible for Whitehorse within the land areas tested. The optimal land area to $CO_2$ tradeoff is at an emission level of 420 kg/kWh. At this emission level, the land area ranges from 1000-5200 ha.

The following plots show the relationships that resulted between land requirements, and unserved demand. In this test, the goal-attainment was used to find designs based on varying $CO_2$ and available land levels. Price was left as unconstrained.

From the section 5.2.2, an unserved demand of about 15% resulted in reasonable price performance for London. Using the results below shown in Figure 29, the projected land requirement at this unserved demand level would be 4900-7900 ha for London. In terms of $CO_2$ emissions, using the mid-point land resource of 6400 ha, London would emit 120-230 kg/kWh (Figure 27).

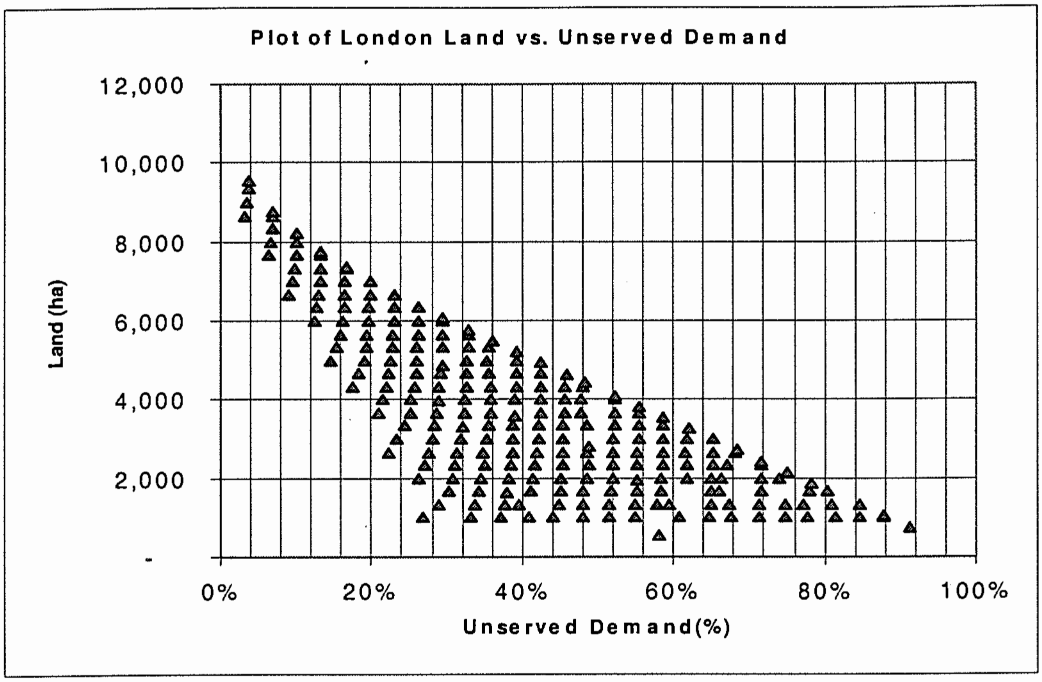

*Figure 29:* *Land area vs. unserved demand for London for land vs. $CO_2$ test.*

Similarly, from section 5.2.2, for Whitehorse an unserved demand of approximately 20% would result in a land requirement of 5000-7400 ha (Figure 30). In terms of $CO_2$ emissions, using the mid-point land resource of 6200 ha, Whitehorse would have $CO_2$ emissions of 170-330 kg/kWh (Figure 28).

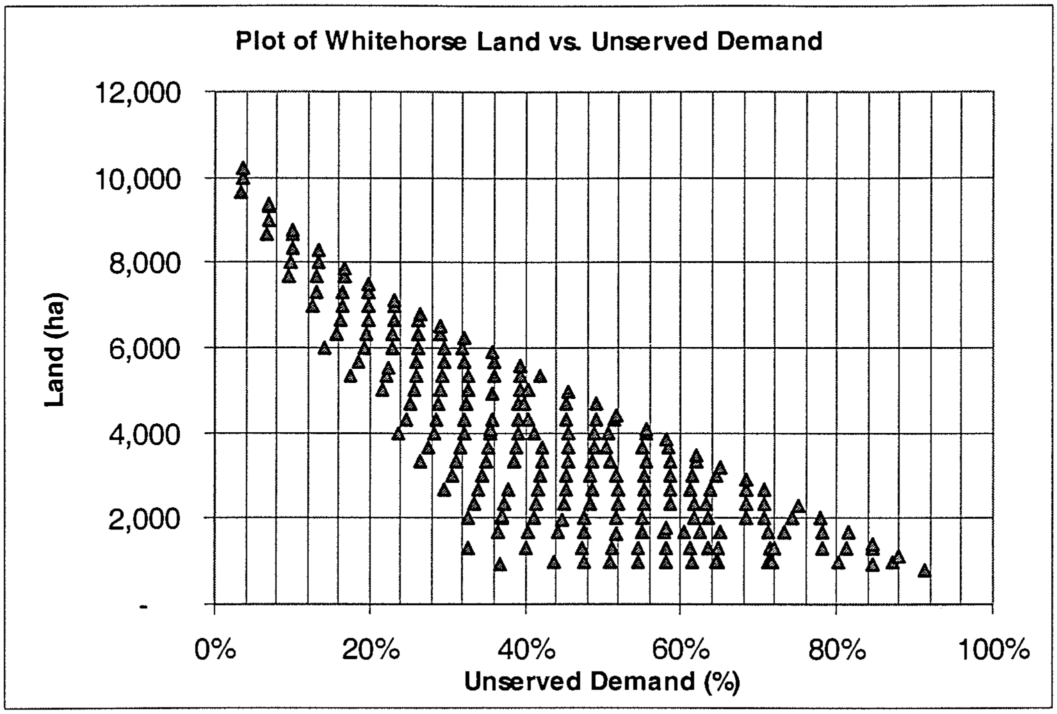

*Figure 30:* *Land area vs. unserved demand for Whitehorse for land vs.* $CO_2$ *test.*

## Computation

There were 900 target points used in generating the results for both London and Whitehorse. Each target point required multiple REOS simulation runs which was driven by the goal-attainment algorithm. On a Pentium 300, with 96 Mb RAM running Windows NT Server 4.0, the total running time was approximately 2 hours per city for the 900 test points. Table 36 summarizes the total REOS iterations run. For any single target, the goal-attainment was limited a maximum of 50 runs for finding a feasible design (in cases where more than 50 runs were required it was assumed that the target point was infeasible).

|  | **London** | **Whitehorse** |
|---|---|---|
| Total Iterations | 17520 | 16504 |
| Number of Test Points | 900 | 900 |
| Feasible Designs Found | 727 | 687 |
| Infeasible Points Tested | 173 | 213 |
| Maximum Iterations For a Run | 50 | 50 |
| Minimum Iterations For a Run | 16 | 16 |

*Table 42: Iterations of simulation required for land vs $CO_2$ tests.*

## Summary of Designs

The following tables give an indication of the power deployment that resulted from the runs of price versus $CO_2$ emissions. The total install is the installed capacity of the entire IRES system (i.e. deployments of wind, solar and biomass). The technology mix is also shown. These average values were calculated from the designs that resulted from the goal-attained regions presented in this section.

| ***London*** | **Total Install ($kW_P$)** | **% Solar** | **% Wind** | **% Biomass** |
|---|---|---|---|---|
| *Average* | 6,723 | 2% | 18% | 80% |

*Table 43: Average IRES install mix for London for land vs. $CO_2$ test*

| ***Whitehorse*** | **Total Install ($kW_P$)** | **% Solar** | **% Wind** | **% Biomass** |
|---|---|---|---|---|
| *Average* | 7,068 | 2% | 18% | 80% |

*Table 44: Average IRES install mix for Whitehorse for land vs. $CO_2$ test*

Overall, the designs that resulted from the goal-attainment were composed of predominantly wind turbine and biomass installed capacities.

### 5.3.3 SENSITIVITY ANALYSIS

The tables below show the sensitivity matrices for both London and Whitehorse (Table 45 and Table 46, respectively). The dominant factor in the sensitivity analysis was the land requirement calculation for the biomass gasification system. Price and unserved demand were not used in the goal-attainment algorithm and were left unconstrained.

| | **Price** | **CO2** | **Land** | **Unserved Demand** |
|---|---|---|---|---|
| **Solar** | 0 | 0.0343 | 0.0000426 | 0 |
| **Wind** | 0 | 0.0251 | 0.000424 | 0 |
| **BIG/GT** | 0 | 0.0343 | 0.196 | 0 |

*Table 45: Sensitivity matrix ($S_{ij}$) for land vs.$CO_2$ tests for London*

| | **Price** | **CO2** | **Land** | **Unserved Demand** |
|---|---|---|---|---|
| **Solar** | 0 | 0.0296 | 0.0000387 | 0 |
| **Wind** | 0 | 0.0216 | 0.000388 | 0 |
| **BIG/GT** | 0 | 0.0682 | 0.191 | 0 |

*Table 46: Sensitivity matrix ($S_{ij}$) for land vs.$CO_2$ tests for Whitehorse*

### 5.3.4 SUMMARY

To reiterate the results from section 5.3.2, the following table summarizes the estimated land requirements and carbon dioxide emissions for London and Whitehorse using an unserved demand of 15% and 20%, respectively. From the design summary in

Table 43 and Table 44, these tests suggest that the dominant technologies for an IRES would be wind and biomass systems.

| | **Land** | **$CO_2$ Emissions** |
|---|---|---|
| *London* | 6400 ha | 120-230 kg/kWh |
| *Whitehorse* | 6200 ha | 170-330 kg/kWh |

*Table 47:Land and $CO_2$ emissions for London and Whitehorse*

The reason that the $CO_2$ emissions are so much less in London than in Whitehorse was due to the fact that London had better wind and biomass resources, and thus its IRES installation was able to achieve a much lower unserved demand, thereby mitigating the use of coal combustion to produce power.

The results of this section assumed that only single-use land utilization was allowed. Dual-use land such as wind farms on agricultural land, was not investigated for its effects on these results. In addition, as was mentioned in previous sections, the overall land use is the total land parcels needed for the technology. Thus, the land for energy cultivation would be dispersed as smaller parcels within a larger contiguous area as suggested in Mann(1996). So, for a dense urban region like London a much larger prospective area would be needed than in a remote locale such as Whitehorse.

## 5.4 SUMMARY OF RESULTS

From the two tests of investigating $CO_2$ emissions with respect to price (Section 5.2) and land availability (Section 5.3), biomass and wind technologies were the dominant technologies. It should be noted that solar photovoltaic installation became significant in highly land-limited (below 4000 ha (Section 5.3.1) ) scenarios in the land versus $CO_2$ tests, but their role was not further investigated because the results from section 5.2 suggested that an unserved demand level of 20% was the most advantageous from a tradeoff between price and $CO_2$ emissions (which was outside the land-limited scenario). The tests of section 5.2 demonstrated that the cost benefits of using coal, could be augmented with the environmentally friendly performance of renewables. In this overall simulated system, introduction of renewables would be able to significantly reduce emissions, while still maintaining reasonable pricing for both Whitehorse and London. Section 5.3 suggested that zero-emission systems were not feasible within the tested limit of 10000 ha of land for either London or Whitehorse.

These results were based on the assumptions of a service price of \$0.05/kWh, an emissions rate of 1027 kg/kWh for coal-based power and an average hourly load demand of 74 kWh (simulated 10 $MW_p$ load). A feasible planning target for London would be a carbon dioxide emissions rate within 150-250 kg $CO_2$/kWh, which would require around 6000-7000 ha of land. This would be accomplished with prices ranging from \$0.05-\$0.11/kWh. The resultant overall electricity regime for the prescribed load would be:

15% Long-term backup
85% Renewables

Similarly, for Whitehorse a feasible planning target would be a carbon dioxide emissions rate of 200-300 kg/kWh with price ranges from $0.05 - $0.11/ kWh. This would result in a land requirement of 6000-7000 ha. An overall electricity regime for the prescribed load would be:

20% Long-term backup
80% Renewables

As a final note, these results are based on an assumed load demand which was taken from a source which was really meant for modelling smaller loads (100 kW range). This translates to a number of possible problems in these results. The first would be that the load may not be indicative of a municipal load for either London or Whitehorse. In addition, the load may not correspond to the geographic load demand that would characterize London and Whitehorse (e.g. heating in winter, air-conditioning in summer). Although, the load curve from Hybrid2 (1997) was from a North American site. These results would suggest that IRES technologies are suitable for both London and Whitehorse, but clearly, the omission of formulating a proper load demand (which was beyond the scope of this study) could have highly unexpected effects on these results. The objective of the study was to demonstrate the methodology, and hence the shortcomings of the data were considered acceptable.

# CHAPTER 6: CONCLUSIONS AND FUTURE WORK

## 6.0 CONCLUSIONS

Energy policy deals with many issues that pertain to the economic, environmental, and social well-being of communities and regions. Many solutions for specific problems; such as long-term sustainable energy programs, affordable and abundant energy supplies, and energy security, deal with specific areas of the problem to the exclusion of other issues. For the policy-maker, this luxury of exclusion is becoming more difficult as the short-comings in existing man-made energy systems becomes more apparent. Issues such as urban air-pollution, global warming, regional scarcities in fuelstocks, nuclear non-proliferation and poverty alleviation, are a few of the problems that national and international policy-making bodies are grappling with in regards to setting energy policies. The scope of engineering design has changed accordingly, and thus, for power systems, many particulars, in addition to economic or technological issues, must be investigated before undertaking long-term projects.

One of the growing movements in electric power systems is the research, development and deployment of solar renewable technologies. Specifically, solar photovoltaics, wind turbines, and dedicated biomass cultivation for thermal electricity generation, have been proposed as candidate technologies for meeting the world's future needs for electricity. These new technologies add to the complexity of policy work because they are highly prone to uncertainties in their power output due to their dual reliance on both facility siting and local climatic conditions. One direct method for dealing with the uncertainty is to use time-series based climatological simulations in order to gauge how well a particular installation will perform. Such models have been available for many years but the computing power to run such models was not readily available. With the advent of high-performance mathematical software systems, the ability to use the simulation in conjunction with other analytic tools has become a reality. The general conclusions of the study fall within two categories; I. Issues in the proposed LCA-based methodology, II. Results from the LCA in studying power systems.

## I. Issues in the LCA Methodology

The LCA is a time-consuming and highly detailed process. One of the most difficult aspects of administering the LCA is to verify results. Strict accounting of materials in production processes is straight-forward but onerous. But, for certain inputs and emissions, time- and site-based models had to be used in order to measure inventory quantities. Verification of these models was a major problem. In this study two main areas of verification were problematic. The first area was verification of models of natural physical processes. The second area was verification of embodied emissions.

Verification of the models for natural physical processes is made difficult by time constraints, data availability, and a lack of expert knowledge of the process. Natural physical processes work on timescales that may span generations of human society. These same processes usually require a large amount of site specific data in order to understand the process in the context of a particular study. Additionally, many natural processes use models that span traditional disciplinary boundaries such as biology, chemistry, physics, and agriculture, so, for reliable verification, an expert appraisal is a necessity unless there exists expert software systems to calibrate the model used in the inventory.

Embodied emissions present a special problem in verification. Using carbon dioxide emissions in a wind turbine rotor as an example, the fiberglass in the rotors proved to be a major contributor to its life-cycle carbon dioxide emissions. Fiberglass manufacture requires large energy inputs. The electricity may be assumed to come off of a shared grid in some industrial centre in the United States. In upper state New York, much of their electrical power comes from Niagara Falls, whereas in the southern United States (such as Texas) fossil fuels are more commonly used for electricity generation. Most of the carbon dioxide from fiberglass is embodied in the electricity input to the overall manufacturing process. Clearly, in this case the rotor's effects on emissions depends on where it was manufactured. This problem becomes even more complicated as the multiple material input streams provide the same raw or intermediate material (such as partially recycled goods like paper or metal parts) because the proportions may not be uniform across all the makes of the same general product. In this study, embodied energy was calculated using only coal-based electricity generation. This approach provided a simple and transparent means to understand the sources of emissions. In a practical application of the LCA, the embodied emissions would be easier to trace because particular products could be evaluated with more detail in their manufacturing processes. The lesson to this situation is that the embodied emissions are significant and cannot be ignored, but care must be taken that unseen bias from these sources do not overly change the results and goals of the study.

## II. Results from the LCA in Studying Power Systems

The goal of this thesis was to demonstrate the efficacy of using goal-attainment algorithms in order to provide indicative results which would be employed in the trade-off analysis for energy policy projects. Special consideration was given to renewable energy system (RES) technologies because of their environmental benefits over fossil-fuel based systems.

The LCA is well-suited to handle the accounting and organization needed to conduct a power study, by its open-ended nature and logical progression in stages. But, problems arise in the implementation of systems which need to assess the aggregate effects of multiple technologies on the same network. Problems such as the cross-effects and network inter-relationships between power output, planned dispatch between multiple sources to multiple loads and material emissions from network facilities must be formally addressed. But, unlike ad hoc and traditional methods, for IRES networks the LCA does help to make the overall study more understandable, holistic, focused and easier to audit than traditional methods such as least-cost planning.

Studies examining embodied effects of products have been conducted for a long time. The LCA provides a malleable and a formalized framework from which industry-to-environment interactions can be classified and examined. Power utility studies employ very large and intricate models. Adding environmental criteria without proper accounting and formalizations courts misinformation within the study. The LCA is information intensive, highly prone to unnoticed shortcuts, implicit assumptions and biases, and difficult to use as an analytic instrument if its open-endedness is abused. But, by incorporating a formal study approach, standard models, well-documented parameterization and inventory results, and accurate process models, very large and transparent software systems can be implemented to analyse these complex systems. Thus, one advantage to using the LCA for studying power utilities, over methods such as least-cost planning, stems from the advent of powerful and accessible computing facilities. The LCA is suited for high-level but in-depth studies that require a prescribed accuracy and clarity, which the interested party is willing to pay for in time, resources and data. Finally, low-level studies that are within more controlled and formal areas of research may be better off using other methodologies because of the information and formalization requirements demanded by an LCA.

Perhaps the most important advantage that the LCA has over other methodologies is that legislation is being brought forth for industries to disclose their emissions. Much of this work is based on the LCA, and thus the LCA would be the best candidate methodology to use in studying problems of industrial environmental effects for this reason alone.

## 6.1 FUTURE RESEARCH

The LCA model for IRES networks contained many potential areas of refinement. The three major functional areas were the inventory, power simulation and goal-attainment system. Below, proposed refinements to the three areas are presented.

### Life-Cycle Inventory (LCI)

(i) Include effects of maintenance, replacement and disposal of generating units on LCI

(ii) Land estimates should reflect appropriated and regional land utilization possibly like the ecological footprint concept [Wackernagel, 1993]

(iii) Introduce dissipation and dispersion models for emissions and possible area of effect of emissions

(iv) Link the inventory results to standard LCA databases such as BUWAL or DEAM for future studies [BUWAL, 1998], [DEAM, 1997]

### Power Simulation

(v) Standard methods which should be included into REOS model:

  - Statistically based load demand forecast models
  - Measures of power system reliability and service using LOLP and LOEP
  - Dispatch models for multiple load demand sinks/power generation sources

(vi) More elaborate economic models could be used to account for:

  - Intra-regional energy supply and demand
  - Biomass importing and exporting

(vii) Disaster and risk management concepts could be used to explore robustness and overall risk associated with system investment

## Goal Attainment

(viii) Use alternate methods for goal-attainment such as genetic algorithms.

# APPENDICES

# APPENDIX A.1: LCI TEMPLATE FOR WIND TURBINES

## *A.1.1 Summary of Materials in Wind Turbine Fabrication*

| **Component** | **Materials** | **Weight** |
|---|---|---|
| Nacelle | Steel | High |
| | Aluminum | Low |
| | Copper | Moderate |
| Tower | Concrete | Moderate |
| | Steel | High |
| Rotors | Fiberglass | Low |
| | Plastics | Low |
| Foundation | Concrete | High |

A typical windmill from the early 1980's would have had a composition of materials as follows:

| |
|---|
| 400 short tons steel |
| 60 tons fiberglass and plastics |
| 10 tons of copper |
| >1 ton of aluminum |
| Concrete foundation estimated at 0.2 of the sum weight of the rest of the structure |

*Materials estimated for a 4 MW installation with a load factor of 0.2 and a lifetime of 10-20 years, [Inhaber, 1981]*

## *A.1.2 Example Commercial Wind Turbine – Jacobs 41/500 Inventory*

### Fabrication Stage

Plant Specifications

| | | | |
|---|---|---|---|
| **Description of Technology:** | Wind Turbine | | |
| **Fuel Type:** | Wind | **Unit Size:** | 500 kW |

*Manufacturer's Specifications*

| | | | |
|---|---|---|---|
| **Manufacturer:** | Jacobs Energie GmbH | **Model No.:** | Jacobs 41/500 |
| **Technology Specific Details:** | Type: | VAWT | |
| | Diameter: | 41 m | |
| | Number of Blades: | 3 | |
| | Power Control | Stall | |
| | Rotor Area | 1320 qm | |
| | Rotor Speed at low windspeed | 18 rpm | |
| | Rotor Speed at high windspeed | 27 rpm | |
| | Location of rotor | Upwind | |
| | Tilt Angle | 4 degrees | |
| | Direction of Rotation | Clockwise | |
| | Cut-in windspeed | 3.2 m/s | |
| | Cut-out windspeed | 20 m/s | |

| | | |
|---|---|---|
| | Survival windspeed | 58 m/s |
| | Hub Height | 50 m |

[Jacobs, 1998]

Material Acquisition Inventory

| **Component Name** | **Materials** | **Weight** |
|---|---|---|
| Rotor Blade | Fiberglass | 1950 kg/blade |
| Nacelle | Steel | High |
| | Aluminum | Moderate |
| | Copper | Low |
| | Total Nacelle | 28000 kg |
| Tower | Steel | 52000 kg |

Specific component weights from [Jacobs, 1998]

## Construction Stage

Siting rules assumes 5 diameters (D) to 10D spacing between adjacent wind mills [Johansson, 1993]. This report will assume a spacing of 5D.

General Land Requirements

| | |
|---|---|
| **Per Unit Install Land Area Required:** | (2.5 x 2x 41m)$^2$ x 3.1415 = 13 ha |
| **Suitability Criteria for Siting Facility:** | - Cut-in windspeed at 3.2 m/s @ 50 m above ground level<br>- Maximum power at 16 m/s @ 50 m above ground level |
| **Required Infrastructure:** | - Access roads for heavy equipment for maintenance<br>- Power transmission cable to interconnect and distribute power |

Regional effects on land-use changes are beyond the scope of this study.

Facility Inventory

| **Construction Stage** | **Facility Part** | **Material** | **Weight** | **Toxicity** | **Price** |
|---|---|---|---|---|---|
| Assembly and erection of tower | Foundation | Concrete | 0.2 of structure | Low | Low |

[Inhaber, 1981]

## Use Stage

*Time Issues*

| | |
|---|---|
| **Time to begin generating power** | Less than one year from construction start |
| **Time to complete construction** | Less than one year from construction start |
| **Useful life of plant** | 20 yrs. |

Reliability figures were not available at the time of this report.

Power Output Simulation Requirements

| | |
|---|---|
| **Dispatch Characteristics** | Immediate dispatch with offloading |
| **Power Type** | AC |
| **Maximum Power** | Rated to 510 kW |

# APPENDIX A.2: LCI TEMPLATE FOR SOLAR PHOTOVALTAIC CELLS

### *A.2.1 Summary of Materials in Solar Photovoltaic Array Fabrication and Construction*

Relative weight, toxicity and prices of input materials to fabricating a PV cell

| **Material** | **Toxic** | **Weight** | **Price** |
|---|---|---|---|
| Quartzite Ore | Low | Very high | High |
| Hydrogen Chloride | Low | Moderate | Moderate |
| Energy (Assuming Fossil-fuel based) | Moderate | Not applicable | High |
| Dopants | High | Very low | High |
| Cleaning Agents (various acids) | Moderate | Low | Low |
| Steel and aluminum | Low | Moderate | Low |

Fabrication Emissions Summary

| **Harmful Emissions** | **Stage** |
|---|---|
| Silica Dust | Sawing wafers |
| Hydrogen Chloride | Quartzite Ore Refinement |
|  | Cleaning Agents |
|  | Wafer surface etching |
| NOx, Sox | Substrate formation |

Construction Materials Summary

| **Material** | **Toxic** | **Weight** | **Unit Price** |
|---|---|---|---|
| Concrete | Low | High | Low |
| Steel Frames | Low | Moderate | Moderate |

Summary of material processing

| **Material** | **Mode** | **Processing** | **Costs** | **Time to dispose** |
|---|---|---|---|---|
| Concrete | Landfilled | Low | Low | Low |
| Steel | Recycled | Moderate | Moderate | Low |
| Glass | Recycled | Low | Low | Low |
| Semi-conductors | Leaching | High | High | Moderate |
|  | Storage | Low | Moderate | Moderate |
|  | Dilution | Low | Low | Moderate |

A typical solar array from the early 1980's would have had a composition of materials as follows:

Estimated per MWyr at a load factor of 0.25

| **Material** | **Weight (tonnes)** |
|---|---|
| Steel | 18.1 |
| Flat Glass | 2.9 |
| Cement | 5.9 |
| Aluminum | 2.9 |
| Semi-Conductor Material | 2.9 |

[Inhaber, 1981]

### *A.2.2 Example Commercial Solar Photovoltaic Array Inventory -- ASE-300-DG/50*

## Fabrication Stage

Plant Specifications

| | | | |
|---|---|---|---|
| **Description of Technology:** | Solar Photovoltaic Flat-plate Silicon Cells | | |
| **Fuel Type:** | Solar Irradiation | **Unit Size:** | 300 W |

Manufacturer's Specifications

| | | | |
|---|---|---|---|
| **Manufacturer:** | ASE | **Model No.:** | ASE-300-DG/50 |
| **Technology Specific Details:** | | | |
| | Cells in array | 216 | |
| | Cell dimensions | 100 mm x 100 mm | |
| | Module Dimensions | 1.89 m x 1.282 m | |
| | Front Glass Thickness | 3.2 mm | |
| | Back Glass Thickness | 3.2 mm | |

[ASE, 1998]

Material Acquisition Inventory

| **Component Name** | **Materials** | **Toxicity** | **Price** | **Weight** |
|---|---|---|---|---|
| Cells | Quartzite Ore | Low | Low | High |
| | Hydrogen Chloride | Low | Moderate | Moderate |
| | Dopants | High | Moderate | High |
| | Cleaning Agents | Moderate | Low | Low |
| | Metal and aluminum | Low | *Low* | *Low* |

## Construction Stage

General Land Requirements

| | |
|---|---|
| **Per Unit Install Land Area Required:** | Assumed to be approximately 6 m²/module<br>2.4 m²/module is actual solar gathering area |
| **Required Infrastructure:** | - No dual use of land for habitat<br>- Transmission to central power conditioning station and inverter(s) for network of solar modules |

Facility Inventory

| **Construction Stage** | **Facility Part** | *Material* | **Weight** |
|---|---|---|---|
| Assembly | Single Array | Aluminum frame, glass plates, semi-conductive cells | 48.2 kg |
| Foundation | Concrete | | 9.6 kg |

[ASE, 1998], [Inhaber, 1981]

**Use Stage**

Time Issues

| | |
|---|---|
| **Time to begin generating power** | Less than one year after construction |
| **Time to complete construction** | Less than one year after construction |
| **Useful life of plant** | Assume long life of 15 yrs |

Power Output Simulation Requirements

| | |
|---|---|
| **Dispatch Characteristics** | Immediate |
| **Power Type** | AC |

# APPENDIX A.3:LCI TEMPLATE FOR BIOMASS INTEGRATED GASIFICATION/GAS TRUBINE

## *A.3.1 Example of an Estimated BIG/GT Inventory*

**Manufacture Stage**

Plant Specifications

| | | | |
|---|---|---|---|
| **Description of Technology:** | Biomass Integrated Gasifier Gas Turbine | | |
| **Fuel Type:** | Gasification of Willow wood | **Unit Size:** | 100 $MW_e$ |

Manufacturer's Specifications

| | | | |
|---|---|---|---|
| **Manufacturer:** | General Electric | **Model No.:** | GE MS-6101FA |
| **Technology Specific Details:** | | | |
| | Type | Combined Gas/Steam Turbine | |
| | Turbine Pressure Ratio | 1:14.9 | |
| | Turbine Firing Temp. | 1288 C | |
| | Steam Cycle Conditions | 10 Mpa/538 degrees C/538 degrees C | |

[Mann, 1996]

## Construction Stage

Component-by-component material breakdowns for the thermal plant were unavailable. The materials for the plant have been aggregated.

Facility Inventory

| **Material** | **Weight** | **Toxicity** | **Price** |
|---|---|---|---|
| Concrete | 230 tonnes | Low | Low |
| Steel | 83 tonnes | Low | Low |
| Aluminum | 650 kg | Low | Moderate |
| Iron | 970 kg | Low | Low |

Adapted from [Mann, 1997, p. 35]

Emissions Summary

| **Material** | **Process** | **Emission** | **Discharge Type** |
|---|---|---|---|
| Particulate | Construction | Dust | Air-borne |
| Ash and Char | Power Generation | Residue | Solid |

## Use Stage

Time Issues

| | |
|---|---|
| **Time to begin generating power** | 4-6 years after plantation + 1 year after construction begins |
| **Time to complete construction** | 2 years |
| **Useful life of plant** | 20 years |

Power Output Simulation Requirements

| | |
|---|---|
| **Dispatch Characteristics** | On-demand with a constant minimal running fuel consumption |
| **Power Type** | AC |

Operation

| **Activity** | **Material** | **Toxicity** | **Weight** | **Price** |
|---|---|---|---|---|
| Fertilizer Use | Nitrogen | Low | 60 kg/ha yr | Low |
| | Phosphates | Low | 15 kg/ha yr | Low |
| | Potassium | Low | 15 kg/ha yr | Low |
| Harvest | Fossil Fuel | Low | 0.5 GJ/Mg of harvested crop | Low-Moderate |
| | Wood Yield | Low | 10-15 Mg/ha yr | Low |

Sources for fertilizer inventory [Hohenstein, 1994], for harvest fossil fuel use [Shapouri, 1995], harvest fossil fuel use [Perlack et al., 1992]

Emissions Summary

| **Material** | **Process** | **Discharge Type** | **Effect** | **Rate** |
|---|---|---|---|---|
| Carbon | Soil Sequestration | Solid | Traps carbon into soil | 1-2 Mg C/ha-yr |

[Cook, 1996]

# APPENDIX A.4: EMBODIED ENERGY AND CARBON DIOXIDE FOR RAW MATERIALS

The following tables are by no means complete life-cycle analyses of the processes and products in question. This study is focused on global warming potentials and the goal is to look at the life-cycle carbon dioxide emissions present in power production. To these ends, these tables summarize some of the factors that contribute to air pollution from various products and are meant only as an instructive example of the type of information requirements that the LCA warrants.

## Steel

Emissions assume the use of scrubbers (99% efficiency) to control the contents of the exhaust from the smelter. Items in *italics* are considered contributors to overall carbon dioxide emissions.

| **Item** | **Rate** | **Source** |
|---|---|---|
| *Energy* | 24-59 GJ/tonne | BRE, 1994 |
| Particulates | 0.75 kg/tonne | USEPA, 1975 |
| Carbon Monoxide | 1.5 kg/tonne | USEPA, 1975 |

## Copper

Emissions assume the use of scrubbers (99% efficiency) to control the contents of the exhaust from the smelter, and the use of other techniques (90% efficiency) to reduce sulfur dioxide emissions. Items in italics are considered contributors to overall carbon dioxide emissions.

| Item | Rate | Source |
|---|---|---|
| *Energy* | 24-59 GJ/tonne | BRE, 1994 |
| Particulates | 0.675 kg/tonne | USEPA, 1975 |
| Carbon Monoxide | Known emission but rate is unknown | USEPA, 1975 |
| Sulfur Dioxide | 62.5 kg/tonne | USEPA, 1975 |

### Aluminum

Assumes zero percent recycled material was used in the processing from ore. In addition, the air-borne emissions includes the emissions from the energy inputs. Items in italics are considered contributors to overall carbon dioxide emissions.

| Item | Rate | Source |
|---|---|---|
| *Thermal energy* | 58.8 GJ/tonne | BUWAL, 1993 |
| *Electricity* | 16.8 GJ/tonne | BUWAL, 1993 |
| Particulates | 37.4 kg/tonne | BUWAL, 1993 |
| Carbon Monoxide | 17.7 kg/tonne | BUWAL, 1993 |
| Sulfur Dioxide | 75.8 kg/tonne | BUWAL, 1993 |

### Concrete (Portland)

Emissions assume the use of scrubbers (50% efficiency for $SO_2$, 98% efficiency for Particulates). According to [USEPA, 1975], which was the most recent documented data found, 3200 kg of raw material was needed to produce 1 tonne of cement. It was stated that 35% of the raw material volume was emitted in the form of water vapour and carbon dioxide. Items in italics are considered contributors to overall carbon dioxide emissions. The water vapour/carbon dioxide emission has been assumed to have a composition of 35% $CO_2$ and 65% water.

| Item | Rate | Source |
|---|---|---|
| *Energy* | 4.3-7.8 GJ/tonne | BRE, 1994 |
| Particulates | 2.4 kg/tonne | USEPA, 1975 |
| *Carbon Dioxide and water vapour* | 1120 kg/tonne | USEPA, 1975 |
| Nitrogen Oxide | 75.8 kg/tonne | USEPA, 1975 |
| Sulfur Dioxide | 2.6 kg/tonne | USEPA, 1975 |

### Glass

The following values assume a minimal recycled material content in the product (<60% of raw materials is discarded glass). These values include the value of emissions from the energy input. Items in italics are considered contributors to overall carbon dioxide emissions.

| Item | Rate | Source |
|---|---|---|
| *Energy* | 6.5 GJ/tonne | BUWAL, 1993 |
| Particulates | 8 kg/tonne | BUWAL, 1993 |
| Sulfur Dioxide | 3.1 kg/tonne | BUWAL, 1993 |

### Fiberglass

The specific life-cycle materials and energy required for fiberglass production were not available at the time of the writing of this report. But, the chemical constituents of construction grade fiberglass were available. The following table is an estimation of the material requirements for fiberglass of the S-class type. Items in italics are considered contributors to overall carbon dioxide emissions.

| Item | Rate | Source |
|---|---|---|
| *Aluminum* | ~250 kg/tonne | Bevier, 1993 |
| *Glass* | ~650 kg/tonne | Bevier, 1993 |
| Magnesium Monoxide | ~100 kg/tonne | Bevier, 1993 |

### Hard Coal Power Plants

Items in italics are considered contributors to overall carbon dioxide emissions.

| **Item** | **Rate** | **Source** |
|---|---|---|
| *Carbon Dioxide* | 1.03 kg/kWh | BUWAL, 1993 |
| Particulates | 0.47 g/kWh | BUWAL, 1993 |
| Sulfur Dioxide | 5.9 g/kWh | BUWAL, 1993 |
| Carbon Monoxide | 1.09 g/kWh | BUWAL, 1993 |
| NOx | 3.16 g/kWh | BUWAL, 1993 |

## Transportation Estimation

$CO_2$ estimates were made from the following assumptions as was done by [Mann, 1996]:

1. Diesel fuel is 85.8% carbon by weight, and that this is converted to emitted $CO_2$ during combustion with a density of 3173 g/gallon.
2. Both trains and trucks use diesel fuel, with an average truck mileage is 5.5 gallons/mile for a fully loaded 18-tonne capacity truck
3. Average energy content of diesel is 140000 Btu/gallon [USEPA, 1975] which is consumed at an overall efficiency of 0.38 [BUWAL, 1993].

Items in italics are considered contributors to overall carbon dioxide emissions.

| **Item** | **Rate** | **Source** |
|---|---|---|
| *Truck* | 2349 Btu/ton-mile | Mann, 1997 |
| *Train* | 589 Btu/ton-mile | Mann, 1997 |

*Summary of Embodied Carbon Dioxide Emissions*

| **Item** | **Rate** |
|---|---|
| *Hard Coal (Electricity)* | 0.343 kg $CO_2$/kWh = 95.54 kg $CO_2$/GJ |
| *Truck Transport* | 0.0442 kg $CO_2$/ton-mile |
| *Train Transport* | 0.0111 kg $CO_2$/ton-mile |
| *Steel* | 2293 – 5637 kg $CO_2$/tonne |
| *Copper* | 2293 – 5637 kg $CO_2$/tonne |
| *Aluminum* | 7232 kg $CO_2$/tonne |
| *Glass* | 621 kg $CO_2$/tonne |
| *Fiberglass* | 2211.65 kg $CO_2$/tonne |
| *Truck* | 0.04418 kg $CO_2$/ton-mile |
| *Train* | 0.01108 kg $CO_2$/ton-mile |
| *Nitrogen Fertilizer* | 576 kg $CO_2$/tonne |
| *Phosphate Fertilizer* | 20 kg $CO_2$/tonne |
| *Potassium Fertilizer* | 2 kg $CO_2$/tonne |
| *Cement (Portland)* | 746 – 1865 kg $CO_2$/tonne |

# APPENDIX A.5: EMBODIED ENERGY AND $CO_2$ CALCULATIONS FOR WIND TURBINES, SOLAR PV AND BIOMASS

**Inventory Calculations for Carbon Dioxide Emissions for IRES Technologies**

**Carbon Dioxide from Coal-based Electricity**

Assume electrical power input and thermal power input are derived from hard coal. [BUWAL, 1993]

| | **CO2 emissions** | | | | |
|---|---|---|---|---|---|
| *Hard Coal (Electricity)* | 0.343 | kg/kWh | = | 95.54 | kg/GJ |

**Transportation Calculations from [Mann, 1996]**

| **Train** | **Truck** | **Units** | |
|---|---|---|---|
| 1400000 | 1400000 | Btu/Gallon | Heat Value in Diesel |
| 0.38 | 0.38 | Eff. | Engine Efficiency |
| 532000 | 532000 | Btu Energy/Gallon | Diesel energy transfer |
| 0.001107143 | 0.004415 | Gallons/ton-mile | Fuel consumption (mass) |
| 0.003512964 | 0.014008795 | kg fuel/ton-mile | Fuel consumption (weight) |
| 0.003021149 | 0.012047564 | kg of C/ton-mile | Fuel consumption (carbon by weight) |
| 0.011078554 | 0.044178416 | kg of CO2/ton-mile | Carbon emissions assuming 100% C to CO2 conversion |
| | 3.667 | C to CO2 Weight Ratio | |
| | 86.00% | % Carbon in Diesel | |
| | 3.173 | kg/gal | Mass of Diesel |

## Embodied Carbon Dioxide Emissions of Raw and Intermediate Materials

| | | | Derived CO2 Emissions | | | |
|---|---|---|---|---|---|---|
| **Material** | **Component** | **Rate** | **Low** | **High** | **Avg.** | |
| *Steel* | Energy | 24-59 GJ/tonne | 2293 | 5637 | 3965 | kg/tonne |
| *Copper* | Energy | 24-59 GJ/tonne | 2293 | 5637 | 3965 | kg/tonne |
| *Aluminum* | Electricity | 58.8 GJ/tonne | 5627 | | | kg/tonne |
| | Thermal | 16.8 GJ/tonne | 1605 | | | kg/tonne |
| *Cement* | Energy | 4.3-7.8 GJ/tonne | 410 | 745 | 577.5 | kg/tonne |
| | CO2 and H20 | 1120 kg/tonne | 336 | 1120 | | kg/tonne |
| *Glass* | Energy | 6.5 GJ/tonne | 621 | | | kg/tonne |
| *Fiberglass* | Aluminum | 250 kg/tonne | 1808 | | | kg/tonne |
| | Glass | 650 kg/tonne | 403.65 | | | kg/tonne |
| *Truck* | Fuel | 2349 Btu/ton-mile | 0.04418 | | | kg/ton-mile |
| *Train* | Fuel | 589 Btu/ton-mile | 0.01108 | | | kg/ton-mile |
| *Nitrogen Fertilizer* | Energy | 0.022 kWh/kg | 0.007546 | | | kg/kg N |
| | Ammonium Production | | 0.5682 | | | kg/kg N |
| *Phosphate Fertilizer* | Overall | | 0.02 | | | kg/kg P |
| *Potassium Fertilizer* | Overall | | 0.002 | | | kg/kg K2O |

**Wind Turbine**

**Unit Size:** 500 kW

*Fabrication Stage*

|  |  |  | kg | kg/unit |  |
|---|---|---|---|---|---|
| **Component Name** | **Materials** | **Weight** | **Total Weight** | **CO2** | **Notes** |
| *Rotor Blade* | Fiberglass | 1950 kg/blade | 5850 | 12938.1525 |  |
| *Nacelle* | Steel |  | 25859 | 102530.935 | Use Inhaber's estimation for |
|  | Aluminum |  | 195 | 1410.24 | the proportions of material |
|  | Copper |  | 1946 | 7715.89 | 400:10:01 |
|  |  |  |  |  |  |
| *Tower* | Steel | 52000 kg | 52000 | 206180 |  |
|  |  |  |  |  |  |
|  |  | **Totals:** | 85850 | 330775.2175 |  |

*Construction Stage*

| **Facility Part** | **Material** | **Weight** | **Total Weight** | **CO2** |
|---|---|---|---|---|
| Foundation | Concrete | 0.2 | 17170 | 15684.795 |
|  |  | of structure |  |  |
| Transportation |  | (distance mi.) |  |  |
|  | Train | 50 |  | 47.5609 |
|  | Truck | 50 |  | 227.57118 |
|  |  | 100 | 17170 | 15959.92708 |

| | | |
|---|---|---|
| **Total Fixed CO2:** | 346735.1446 | kg/unit |
| **Total Variable CO2:** | 0 | kg/unit |
| **Total Fixed CO2:** | 0.122636088 | t/m2 windswept |

**Solar Photovoltaics**

| | | | **CuInSe** | **Silicon** | |
|---|---|---|---|---|---|
| **Material** | **Weight Ratio** | **kg/unit** | **g CO2/unit** | **g CO2/unit** | |
| Steel | 18.1 | 32.01541284 | 126941.1119 | 126941.1119 | |
| Flat Glass | 2.9 | 5.129541284 | 3185.445138 | 3185.445138 | |
| Cement | 5.9 | 10.4359633 | 9533.252477 | 9533.252477 | |
| Aluminum | 2.9 | 5.129541284 | 37096.84257 | *37096.84257* | |
| Semi-Conductor Material | 2.9 | 5.129541284 | 139450.766 | 371868.7093 | (a),(b) |
| **Totals** | 32.7 | 57.84 | 316207.4181 | 548625.3614 | |
| | | **kg CO2/unit:** | 316.2074181 | 548.6253614 | |
| | | **Array Area:** | 2.47 | m2 | |
| | | **Per Unit Area Emission Estimation:** | 0.128019198 | 0.222115531 | t CO2/m2 |

Assume transport and discard are negligible

| | | |
|---|---|---|
| (a) | [Furlan, 1989] | Energy requirements for CIS cell production, estimated energy needs for silicon based on [Furlan, 1989] energy estimate and [Markvaart, 1993] ratio of CIS to Si |
| (b) | [Inhaber, 1981] | Proportions of materials used in a solar array, ASE gave only the total array weight w/out foundation |

| *Markvaart Calculation* | | | |
|---|---|---|---|
| | 235 | kWh/m2 | Assumed energy production per ann. in a 1.5MWp install |
| | 2.68265E-08 | GWyr/m2 | Convert per annum per unit area to other units |
| | 400000 | t CO2/Gwyr | Final reported emissions from Palz and Zibetta [Zibetta, 1992] |
| | 0.010730594 | t CO2/m2 | Per unit area emissions estimation used in Markvaart |

*Note:* *Very low per unit area emissions estimation compared to Inhaber*

*Probably means that means of production have radically changed in the last 20 years*

| **Biomass** | [Mann, 1996] | | | |
|---|---|---|---|---|
| Plant Specifications | Biomass Integrated Gasifier Gas Turbine | | Efficiency: | 0.15 |
| | Fuel Type: | Gasification of Willow wood | Unit Size: | 100 MWe |

| Facility Inventory | | | |
|---|---|---|---|
| **Material** | **Weight** | | **CO2 (kg/plant)** |
| *Concrete* | 230 | tonnes | 210105 |
| *Steel* | 83 | tonnes | 329095 |
| *Aluminum* | 650 | kg | 4700.8 |
| *Iron* | 970 | kg | 3846.05 |
| Truck Transport (50 mi) | 50 | | 694.9706635 |
| *Train Transport (50 mi)* | 50 | | 174.2767397 |
| **Totals** | 314.62 | tonnes | 548616.0974 |

Adapted from [Mann, 1996, p. 35], Assumed iron and steel used the same CO2 emission rates

| **Operation** | | | | CO2 | | |
|---|---|---|---|---|---|---|
| **Activity** | **Material** | **Weight** | **Units** | **Low** | **High** | **Units** |
| *Fertilizer Use* | Nitrogen | 60 | kg/ha-yr | 34.54476 | | kg/ha-yr |
| | Phosphates | 15 | kg/ha-yr | 0.3 | | kg/ha-yr |
| | Potassium | 15 | kg/ha-yr | 0.03 | | kg/ha-yr |
| *Harvest* | Fossil Fuel | 0.5 | GJ/Mg wood | 0.28049122 | 0.42073683 | kg CO2/ha-yr |
| | Wood Yield | 10-15 | Mg/ha-yr | | | |
| *Liquefaction* | Fuel Yield | 4.7 | MWh/t wood | | | |
| *Transport* | 27 mi. by truck | 0.04418 | kg CO2/ton-mi | 11.9286 | 17.8929 | kg CO2/ha-yr |

Source for Willow Fuel Yield [Ledin, 1996a], fertilizer [Hohenstein, 1994], harvest fuel use [Shapouri, 1995] and [Perlack, 1992]

| **Emissions Summary** | | | CO2 | | |
|---|---|---|---|---|---|
| **Material** | **Process** | **Rate** | **Low** | **High** | **Units** |
| *CO2* | Power Generation | | 0.332 | | kg CO2/kWh |
| *Carbon* | Soil Sequestration | 1-2 Mg C/ha yr | 3.667 | 7.334 | Mg CO2/ha-yr |

Source for soil sequestration [Cook, 1996]

| | | | Low | High | Average | Units |
|---|---|---|---|---|---|---|
| **Summary** | **Fixed CO2** | Plant Construction | | 548616.0974 | 548616.0974 | kg CO2/plant |
| | **Variable CO2** | Cropping | 47.08385122 | 53.18839683 | 50.13612403 | kg CO2/ha-yr |
| | | Soil Sequestering | -3.667 | -7.334 | -5.5005 | t CO2/ha-yr |
| | | Electricity Generation | 0.332 | | 0.332 | kg/kWh |

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