EVALUATING THE SUSTAINABILITY OF AN ECOMIMETIC ENERGY SYSTEM: 
AN ENERGY FLOW ASSESSMENT OF SOUTH CAROLINA

by

James Alexander Russell

Bachelor of Science
Clemson University, 1994

Master of Engineering
University of South Carolina, 2002

--------------------------------
Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy in the
Department of Mechanical Engineering
College of Engineering and Information Technology
University of South Carolina

2004

Department of Mechanical Engineering
Major Professor  Department of Mechanical Engineering
Committee Member

Department of Mechanical Engineering
Committee Member  Dean of the School of the Environment
Committee Member

Dean of the Graduate School
DEDICATION

For my father who always encouraged me to ask why

and never tired of answering when I did.
ACKNOWLEDGEMENTS

I begin by acknowledging my family and friends. Family provides the beginning and basis for all future interactions. My family members, though not directly involved in this endeavor, were the primary architects of my early days and therefore have strongly influenced my current path. Friends, of course, make up a large component of the support and community structure after one leaves early family life. Thanks to my friends and family for their support. Special thanks to my fiancé, Molly Best, for her support and understanding during this sometimes difficult journey.

Next I thank the State of South Carolina. As a native child and current resident of South Carolina, the opportunities that I have had have been provided in large part by this state. I hope that South Carolina will continue to offer opportunities for all others who desire to gain knowledge. I also hope that some of the information in this dissertation can help move the state towards a more sustainable path.

Many thanks to Archie Adams, former supervisor and colleague, for early career guidance, advice, and encouragement. Thanks to Ferol Vernon for support early in my graduate years. Thanks to the Department of Mechanical Engineering which has housed me (sometimes it seemed literally) for the past four years.

Thanks to the entire lineage and legacy of the Laboratory for Sustainable Solutions (LSS). Thanks to those LSS’ers who came before me; Tom Wallace, Emily Peterson, David Grigg, Sirrine Saleem, Beth Locklear, and Lynn Odom; and set the stage upon which I “strut and fret.” Thanks also to those with whom I currently work; Nadia Craig, Veronica Addison, and Sylvi Lombard; for you daily support. Thanks especially
to Wally Peters, for founding the LSS, inviting me to learn, and encouraging the entire process.

Lastly, thanks to my committee; Adbel Bayoumi, Bruce Coull, Jamil Khan, and Wally Peters; for their time and critical input.
ABSTRACT

Industrial ecology has been defined “as the means by which a state of sustainable development is approached and maintained.” Some proponents of industrial ecology see it as a useful analogy which can inform technological system design in an incremental manner. Others see industrial ecology as a powerful metaphor which should transform technological systems, remaking them in the image of natural systems by using fundamental ecosystem characteristics as a template to create an ecosystem mimicking or ecomimetic technological system.

This work studies energy flows through technological and natural systems in South Carolina. Fundamental ecosystem energy flow characteristics are defined and measurable metrics for ecological sustainability, which is one component of sustainability or sustainable development, are developed. Energy flow assessments of past and present human and natural systems in South Carolina are carried out and are used to develop an ecomimetic model.

The ecomimetic model based on South Carolina’s current energy flows is not sustainable as measured by the defined metrics of ecological sustainability. A second model using reduced energy flows based on the energy consumption of an energy efficient world class benchmark country is also a failure based on the metrics of ecological sustainability. Based on this study of South Carolina, industrial ecology cannot be used as a metaphor to create sustainable, ecomimetic systems given current patterns and rates of energy consumption. By altering the energy mix away from liquid fuels and towards solar energy, a sustainable model can be created.
I'm on my way, I'm making it
I've got to make it show, yeah
so much larger than life
I'M going to watch it growing

the place where I come from
is a small town
they think so small
and use small words

but not me
I'm smarter than that
I worked it out
I've been stretching my mouth
to let those big words come right out

I've had enough, I'm getting out
to the city, the big big city
I'll be a big noise with all the big boys
so much stuff I will own
and I will pray to a big god
as I kneel in the big church

big time
I'm on my way-I'm making it
big time big time
I've got to make it show yeah
big time big time
so much larger than life
big time
I'm going to watch it growing
big time

my parties have all the big names
and I greet them with the widest smile
tell them how my life is one big adventure
and always they're amazed
when I show them round my house to my bed
I had it made like a mountain range
with a snow-white pillow for my big fat head
and my heaven will be a big heaven
and I will walk through the front door
big time
I'm on my way-I'm making it
big time big time
I've got to make it show-yeah
big time big time
so much larger than life
I'm going to watch it growing
big time big time
my car is getting bigger
big time
my house is getting bigger
big time
my eyes are getting bigger
big time
and my mouth
big time
my belly is getting bigger
big time
and my bank account
big time
look at my circumstance
big time
and the bulge in my big big big big big big big

Peter Gabriel, “Big Time (suc cess),” So
TABLE OF CONTENTS

DEDICATION PAGE ................................................................................................................ii

ACKNOWLEDGEMENTS ......................................................................................................... iii

ABSTRACT ................................................................................................................................. v

PREFACE ...................................................................................................................................... vi

TABLE OF CONTENTS ............................................................................................................ viii

LIST OF TABLES ...................................................................................................................... x

LIST OF FIGURES ................................................................................................................... xii

1. INTRODUCTION .................................................................................................................. 1
   1.1. General Introduction to the Problem ................................................................. 1
   1.2. A Brief History of the Problem ........................................................................ 2
   1.3. The Birth of Industrial Ecology ................................................................. 5
   1.4. Research Objectives and Hypothesis ......................................................... 7

2. LITERATURE REVIEW ..................................................................................................... 9
   2.1. An Overview of Ecosystems ............................................................................. 9
   2.2. An Overview of Industrial Ecology .......................................................... 16
   2.3. An Overview of Sustainability/Sustainable Development ....................... 21
   2.4. Synthesizing the Principles of BE, IE, and SD: Creating a Common Language 22
   2.5. Synthesizing the Principles of BE, IE, and SD: Creating Metrics ............... 29

3. METHODOLOGY ........................................................................................................... 37
   3.1. Boundaries ........................................................................................................... 37
   3.2. Tools and Data .................................................................................................... 37
LIST OF TABLES

Table 1.1: History of Selected Environmental Events and Legislative Responses .......... 5
Table 2.1: Ecological Definitions and Generalized Definitions ..................................... 23
Table 3.1: Comparison of Land Areas from Various Sources ....................................... 39
Table 4.1: Current SC Land Cover and NPP .................................................................. 43
Table 4.2: Estimate of SC Land Cover and NPP for the Pristine Age ......................... 45
Table 4.3: Summary of Key Metrics Pristine Age ......................................................... 47
Table 4.4: Conversion of Land for Agricultural Use ..................................................... 49
Table 4.5: Estimated SC Land Cover and NPP for Agricultural Age ............................. 50
Table 4.6: Summary of Key Metrics Pristine and Agricultural Ages ............................. 51
Table 4.7: SC Exports in 2000 ..................................................................................... 52
Table 4.8: Energy Consumption by Industry based on Employees .............................. 64
Table 4.9: Livestock Production Data for 2000 ............................................................. 80
Table 4.10: Seafood Catch Data for 2000 ................................................................... 81
Table 4.11: Summary of Key Metrics Pristine, Agricultural, and Industrial Ages ......... 83
Table 5.1: Allocation of Tree NPP .................................................................................. 87
Table 5.2: Approximate Nutrient Content of Selected Forages ..................................... 88
Table 5.3: Petroleum Products to be Replaced by Biodiesel ......................................... 96
Table 5.4: Summary of Land Areas Required for Status Quo Model ............................. 98
Table 5.5: Per Capita GDP of Selected Countries ......................................................... 99
Table 5.6: Comparison of Key Energy Metrics from Selected Countries ..................... 100
Table 5.7: Summary of Land Areas Required for World Class Benchmark Model ...... 103
Table 5.8: Summary of Land Areas Required for Sustainable, Ecomimetic Model ..... 105
Table 5.9: Summary of Key Metrics Pristine, Agricultural, Industrial, and Model ..... 106
LIST OF FIGURES

Figure 1.1: World Population (1AD to 2050AD) .............................................................. 3

Figure 2.1: Simplified energy flow and material cycling through and ecosystem ........ 12
Figure 2.2: Simplified energy flow and material cycling among producers, consumers, and decomposers ........................................................................................................................................... 13
Figure 2.3: A five-kingdom system based on three levels of nutrition ....................... 14
Figure 2.4: Digraph of Energy Flow Through and Ecosystem ....................................... 30
Figure 2.5: Digraph of Energy Flows in the Biotic/Anthropic System ......................... 32
Figure 3.1: Land Use in South Carolina Compiled from 1990 SPOT Data .................... 38
Figure 4.1: Digraph of Energy Flow in the Pristine Biotic/Anthropic System ............. 46
Figure 4.2: Digraph of Energy Flows in the Agricultural Biotic/Anthropic System ...... 50
Figure 4.3: Technical Energy Consumption in SC 1900-2000 ...................................... 54
Figure 4.4: Technical Energy Flow in the United States year 2000 ............................... 55
Figure 4.5: Technical Energy Flow in South Carolina year 1999 ................................. 56
Figure 4.6: Technical Energy Consumption in the Residential Sector ....................... 58
Figure 4.7: Technical Energy Consumption in the Commercial Sector ....................... 59
Figure 4.8: Residential Energy Use Density ................................................................. 60
Figure 4.9: Commercial Energy Use Density .............................................................. 61
Figure 4.10: SC County Level Population Data ............................................................ 62
Figure 4.11: Technical Energy Consumption in the Industrial Sector .......................... 63
Figure 4.12: Industrial Sector Energy Consumption Model vs. EIA Data .................... 65
Figure 4.13: Industrial Sector Energy Consumption Adjusted Model vs. EIA Data ....... 67
Figure 4.14: Industrial Energy Use Density ................................................................. 68
Figure 4.15: County Level Industrial Sector Energy and Employment ...................... 69
Figure 4.16: Energy Consumption in the Transportation Sector .............................. 70
Figure 4.17: County Level Motor Gasoline Consumption Weighted by Commute Time 71
Figure 4.18: County Level Motor Gasoline Consumption Density ............................ 72
Figure 4.19: County Level Diesel Fuel Consumption .................................................. 73
Figure 4.20: County Level Diesel Fuel Consumption Density ..................................... 74
Figure 4.21: Energy Inputs at Electric Utilities by Fuel Type ....................................... 75
Figure 4.22: Electricity Produced by Utilities by County ............................................. 76
Figure 4.23: County Level Percentage of FEC ............................................................. 77
Figure 4.24: County Level Energy Consumption Density ........................................... 77
Figure 4.25: NPP in SC per 1990 SPOT Data ............................................................ 78
Figure 4.26: Map of Urban, Agricultural, and Scrub/Shrub Land Cover ..................... 79
Figure 4.27: Digraph of Energy Flows in the Industrial Biotic/Anthropic System ....... 83
CHAPTER ONE
INTRODUCTION

Blessed are the poor, for they shall inherit the earth

Better to be poor than a fat man in the eye of a needle

And as these words were spoken I swear I hear The old man laughing

'What good is a used up world, and how could it be worth having'

Sting

1.1 General Introduction to the Problem

In short, the problem is that modern human population growth is exponential. This type of population growth resembles bacterial reproduction in a latrine or an algal bloom in a eutrophic pond. Both of these systems are maintained at higher energy levels by energy subsidies and both will drop back to a lower energy state when that subsidy wanes. Energy subsidies are common in nature; some of the most productive ecosystems exist at elevated energy levels due to energy subsidies. Salt-marshes and wetlands, both very productive systems, depend on energy subsidies. Both are subsidized by the energetic input of periodic flooding. Subsidies are not inherently problematic, but can become a problem for the ecosystem they support when they end. This study is not a political treatise about the evils of energy subsidies; energy consumption and the resulting egesta are necessary for life. The act of living, on a fundamental level involves
maintaining a corporeal existence at a far from equilibrium state by degrading a high quality energy source or food into lower quality energy and some material waste products (Margulis and Sagan, 1995). However, this study will critically examine the source and size of South Carolina’s energy subsidies, the concomitant energy flows, and determine whether or not the resultant system is sustainable.

1.2 A Brief History of the Problem

It is believed that life has become the victim of its own success at least twice during its evolution. The first was a crisis of energy supply due to the success of the early anaerobes. As these first creatures multiplied the primordial stockpile of food was depleted. This crisis was solved with the evolution of photosynthesis. The second was a crisis of waste production due to the success of the photosynthesizers. As photosynthesizers increased in numbers their waste product, oxygen, began to accumulate in the environment. This crisis was solved through the evolution of respiration (Margulis and Sagan, 1995). The modern human situation may or may not be a crisis of both energy supply and waste production depending upon the reactions of the earth system and the human system. The following is a brief summary of the evolution of the current human situation.

About 100,000 years ago our species, Homo sapiens or the wise human, first walked the face of the earth (Lamb and Sington, 1998). For the next 90,000 years or so prior to the agricultural revolution, humans lived as hunter-gatherers with a total population that was probably no larger than five million individuals (Deevy, 1960). The metabolism of a hunter-gatherer consists of food for bodily metabolism and also an extended or external metabolism of biomass for tools, clothing, shelter, and fire (Haberl,
2001). This external metabolism is the sum of all non-physiological human consumption. About 11,000 years ago agriculture became common allowing humans to increase their population densities (Diamond, 1999). The bodily metabolism of an agrarian is the same as a hunter-gatherer, but agrarians also grow crops and feed domesticated animals giving them a larger external metabolism (Fischer-Kowalski and Haberl, 1997). The human population and its total metabolism has continued to grow, the most recent and largest population explosion coincides with the industrial revolution which began about 300 years ago, see figure 1.1 below.

![World Population: 1 AD to 2050 AD](image)

Figure 1.1: World Population (1 AD to 2050 AD) data from (McEvedy and Jones, 1978)

The industrial revolution resulted in a large increase in external metabolism. This increase in energy inputs resulted in equally large outputs of waste products. The industrial revolution is different energetically from the agricultural revolution not just in the quantity of consumption but also in the source of energy. The industrial revolution has been driven by non-renewable fossil fuels created millions of years in the past.
As the human population and its cumulative internal metabolism grew and as the external metabolism, required first by the agricultural and next by the industrial revolution grew, there came a point when the impacts of the energy use and waste production began to be noticed and the environmental movement was born.

Reviewing the history of environmental concerns and environmentalism in the United States, environmental pioneers such as Henry David Thoreau, George Perkins Marsh, John Muir, and Aldo Leopold were active during the 1800’s and early 1900’s. From these pioneers came a sense of value for nature and wilderness; and a conservation ethic that has created a sense of awareness of issues involving resource use, inspiring the creation of national parks and legislation such as the Endangered Species Act (Leopold, 1949; Walden; Thoreau, 1995; Russell, 1968).

In the 1960’s, Rachel Carson focused attention on a new concern, hazardous chemicals, pollution and its effects on humans and animals (1962). This concern for toxics and waste has been another dominant area of concern for environmentalists since the 1960’s. A review of environmental disasters yields familiar stories; DDT, the Cuyahoga River burning, Love Canal and Hooker Chemical, Bhopal, Three Mile Island, Chernobyl, and the Exxon Valdez. Table 1.1 below provides a review of selected environmental incidents, milestones, and legislative responses.
<table>
<thead>
<tr>
<th>Year</th>
<th>Events and Legislation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962</td>
<td>Carson’s <em>Silent Spring</em> is published (examines DDT as a major concern)</td>
</tr>
<tr>
<td>1969</td>
<td>Cuyahoga River catches fire</td>
</tr>
<tr>
<td>1970</td>
<td>First Earth Day/ EPA is founded, Clean Air Act (CAA)</td>
</tr>
<tr>
<td>1972</td>
<td>UN Conference: Human Environment (Stockholm)/ Clean Water Act (CWA)/ EPA bans DDT</td>
</tr>
<tr>
<td>1973</td>
<td>Endangered Species Act/ EPA begins leaded gasoline phase out</td>
</tr>
<tr>
<td>1974</td>
<td>Safe Drinking Water Act (SDWA)</td>
</tr>
<tr>
<td>1975</td>
<td>Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)</td>
</tr>
<tr>
<td>1976</td>
<td>Resource Conservation and Recovery Act (RCRA- concerns about PCB’s)/ Toxic Substance Control Act (TSCA)</td>
</tr>
<tr>
<td>1978</td>
<td>Love Canal is evacuated</td>
</tr>
<tr>
<td>1979</td>
<td>Three Mile Island incident/ EPA sues for Love Canal clean up and bans PCB manufacturing</td>
</tr>
<tr>
<td>1980</td>
<td>Comprehensive Environmental Responsibility and Liability Act (CERLA or Superfund- cradle to grave responsibility for hazardous substances driven by Love Canal)</td>
</tr>
<tr>
<td>1985</td>
<td>Bhopal Union Carbide leak</td>
</tr>
<tr>
<td>1986</td>
<td>Chernobyl meltdown/ Environmental Protection and Community Right to Know Act (EPCRA- driven by fears of Bhopal)</td>
</tr>
<tr>
<td>1989</td>
<td>Exxon Valdez oil spill/ Brundtland Report “Our Common Future” (defines sustainable development)</td>
</tr>
<tr>
<td>1990</td>
<td>Pollution Prevention Act (prevent pollution at the source—a move away from “end of pipe” focus)</td>
</tr>
<tr>
<td>1992</td>
<td>Earth Summit in Rio (focus on climate change, biological diversity, forest management, and sustainable development/ Agenda 21)</td>
</tr>
<tr>
<td>1993</td>
<td>EPA orders phase-out of CFC’s</td>
</tr>
<tr>
<td>1994</td>
<td>EPA rolls out Energy Star Labeling</td>
</tr>
<tr>
<td>1997</td>
<td>Kyoto Protocol</td>
</tr>
<tr>
<td>2002</td>
<td>Earth Summit in Johannesburg</td>
</tr>
</tbody>
</table>

Table 1.1: History of Selected Environmental Events and Legislative Responses

Conservation and pollution issues have remained salient topics and various disciplines have developed to address them. One such discipline is industrial ecology.

1.3 The Birth of Industrial Ecology

The birth of industrial ecology combined the two main concerns of the environmental movement, conservation and pollution into a single concept inspired by ecosystem structure and function. In 1989, Robert Frosch and Nicholas Gallopoulos, both employees at General Motors, brought the concept of industrial ecology into the academic limelight with their journal paper “Strategies for Manufacturing: Wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment.” Frosch and Gallopoulos state in this paper that
“the traditional model of industrial activity…should be transformed into a more integrated model: an industrial ecosystem.” The authors further state that “the industrial ecosystem would function as an analogue of biological ecosystems.” IE with a focus on pollution prevention was a dramatic break from traditional command and control schemes and end-of-pipe solutions to pollution control. However IE, as a fledgling field, is not without its weaknesses. Two of the weaknesses are its lack of focus on energy flows and lack of a universally accepted definition (O’Rourke et al, 1996).

To date, IE has provided a limited analysis of energy issues. Energy flows are vital to all non-equilibrium systems and have been studied extensively by ecologists (Odum, 1957; Teal, 1957; Lindeman, 1942; Pimm, 1982). Industrial or socioeconomic metabolism, a core concept of IE, is defined as the study of material and energy flows within human societies and between them and their natural environment (Krausmann and Haberl, 2002). Both flows are important and both must be studied for an understanding of the system. In the 1970’s energy flows became a prominent topic of study. Howard T. Odum foresaw problems related to modern society’s fossil energy subsidy (1971). After the oil embargo of 1973, many others recognized the issue and several books were published delving into energy flow issues (Cook, 1972; Romer, 1976; Odum and Odum, 1976; Green, 1978; Pimentel and Pimentel, 1979; Lockeretz, 1976). Some authors such as Pimentel and Odum continued to publish on the energy topic. However, among the ranks of industrial ecologists, mass flow assessment has become the dominant research focus of modern industrial metabolism work (Krausmann and Haberl, 2002).

A second weakness of IE is that as a concept it is poorly defined. Several definitions have been put forward but, similar to the concept of sustainability; a
A universally agreed upon definition of the concept has not yet emerged. One of the manifestations of this lack of a universal definition is the debate within the field between those who see IE as a useful analogy which can inform human system design in an incremental way and those who see IE in a more metaphorical sense as a vision that can transform human systems remaking them in the image of natural systems (O’Rourke et al, 1996). This debate has yet to be resolved, in fact one session of the inaugural meeting of the International Society of Industrial Ecology held in 2001 was titled “Industrial Ecology: Analogy or Metaphor” and was devoted to exploring this topic. A lively debate ensued with the four presenters and several participants from the audience disagreeing vociferously on the question.

Industrial ecology is a grand concept which has the potential to be much more than a concept. IE has been touted as the means by which humanity can reach a state of sustainability (Allenby, 1992). However, the lack of an energy flow focus and a universal definition do not reinforce this claim.

1.4 Research Objectives and Hypothesis

This study seeks to address IE’s lack of focus on energy flows and lack of a universal definition. The study will directly address the lack of energy flow assessments by carrying out a detailed energy flow assessment of South Carolina. Also, energy flow models for human systems based on design principles of natural systems will be created. These models will be employed to determine if the metaphor of natural systems is useful or misleading when applied to the design of human systems. These model systems will be referred to as ecomimetic systems, which can be defined as systems that mimic ecosystems.
More specifically this study seeks to carry out an energy flow assessment of past and present patterns of energy flow through both the natural and human systems bounded by the present borders of South Carolina and establish whether the fundamental architecture of natural system energy flows can serve as a template to create a sustainable energy system for South Carolina.

The energy flow assessment will include input-output models of past and present energy flows in natural and human systems and modeling of spatial distributions (energy densities) of the present energy production and consumption in natural and human systems.

Before these models can be created a framework must be developed to guide the modeling process. This framework must include a distillation of the fundamental architecture of the energy flows in natural systems and a quantifiable definition of what is sustainable. To begin this process, a general understanding of ecosystems, industrial ecology, and sustainability/sustainable development is required. The following chapter provides brief reviews of the three topics. An attempt is also made in the following chapter to create a common language bridging industrial and biological ecology. Finally, the required modeling framework is developed in the last section of chapter two.
CHAPTER TWO

LITERATURE REVIEW

A book is a means of communication—communication of information, of rules, of thoughts. Its tools are the symbols of language—numbers, words, terms. Tools in continual use tend to become blunted and need resharpening if they are to remain useful. Obsolete tools, unfit to serve new tasks, must be refitted or be discarded. Thus, tasks and tools must be kept in step in their developments.

Paul Weiss

2.1 An Overview of Ecosystems

The idea of an ecosystem is a core concept in ecology. Allaby proposes the following definition of the term ecosystem (1998):

An ecosystem is “a discrete unit that consists of living and non-living parts, interacting to form a stable system. Fundamental concepts include the flow of energy via food-chains and food-webs, and the cycling of nutrients biogeochemically. Ecosystem principles can be applied at all scales. Principles that apply to an ephemeral pond, for example, apply equally to a lake, an ocean, or the whole planet. In Soviet and central European literature ‘biogeocoenosis’ describes the same concept.”
This is a powerful concept, especially the concept of universal scale applicability. The living components of ecosystems are organisms. All organisms can be divided into two groups, autotrophs and heterotrophs. This is a functional division is based on the manner by which organisms obtain nutrition. The autotrophs or “self-feeders” provide the energy basis for all other life; they receive their energy flow from inorganic sources, while the heterotrophs or “other-feeders” receive their energy flow from the autotrophs (Allaby, 1998).

Autotrophs, also known as producers, can be divided into two groups, the photosynthesizers and the chemosynthesizers. The photosynthesizers use electromagnetic energy in the form of sunlight. Chemosynthesizers use chemical energy usually in the form of reduced mineral compounds (Rambler et al, 1989). The autotrophs use the energy input to organize simple inorganic compounds such as carbon dioxide and water into more complicated biological compounds such as hydrocarbons, lipids, and proteins (Ricklefs, 1983). Although the chemosynthesizers are believed to be the first life on the planet (Ashworth, 1991), they are now far outnumbered by the photosynthesizers and contribute little to the overall energy flow of the biosphere (Lieth and Whittaker, 1975).

The heterotrophs can also be divided into two main groups, the consumers and the decomposers. Consumers receive their energy flow by ingesting living or dead organic matter. Decomposers (fungi and most bacteria) receive their energy flow by absorption. Decomposers break down organic matter into inorganic matter, absorbing the nutrients they need while releasing the remaining material for re-use by the producers (Odum, 1983).
Figure 2.1 below is a simplified representation of material and energy exchanges in an ecosystem highlighting the interactions between autotrophs and heterotrophs. The autotrophs capture energy (sunlight) and use it to drive a reaction between carbon dioxide (CO$_2$) and water that creates hydrocarbons (C$_6$H$_{12}$O$_6$) and diatomic oxygen (O$_2$). The energy rejected as low quality heat by the autotrophs due to photosynthetic losses and other metabolic activity is represented as the respiration energy flow. The autotrophs are carrying out an energy conversion process where sunlight is converted into chemical energy and stored as biomass. This created biomass is referred to as net primary productivity (NPP) and can be defined as the energy fixed or assimilated by autotrophs minus autotrophic respiration (Vitousek et al, 1986). The total energy fixed by autotrophs prior to their respiration losses is known as gross primary productivity (GPP).

The biomass created by the autotrophs is consumed either directly or indirectly by heterotrophs. The chemical energy stored in the biomass is released through oxidation and used to drive heterotrophic metabolism, which is the reverse of the biomass creation and is carried out through the combination of hydrocarbons with diatomic oxygen with the subsequent release of energy and carbon dioxide. These photosynthesis-oxidation reactions set up a balanced material exchange of carbon dioxide and diatomic oxygen between the autotrophs and heterotrophs. Heterotrophs also reject low quality heat energy through respiration. Heterotrophic created biomass is referred to as secondary productivity (SP) and can be defined as the energy assimilated by heterotrophs minus heterotrophic respiration (Odum, 1983).
All life is made up of the same basic elements; carbon, hydrogen, oxygen, nitrogen, phosphorous, and sulfur. The carbon, hydrogen, and oxygen are cycled between autotrophs and heterotrophs by the carbon dioxide and diatomic oxygen exchange. The nitrogen, phosphorous, and sulfur are cycled as well. The heterotrophs obtain nitrogen, phosphorous, and sulfur from the tissues of autotrophs. The autotrophs obtain these same elements through the work of a specialized group of heterotrophs, the decomposers. Decomposers take any dead tissue (autotrophic or heterotrophic) and break it down into simple inorganic compounds. The decomposers absorb the nutrients they need and the remaining matter (containing nitrogen, phosphorous, and sulfur) is available again for the autotrophs (Odum, 1983).

Figure 2.2 below provides a graphic of these processes showing the decomposers separated from the other heterotrophs. For clarity, the heterotrophs that function by ingestion (herbivores, carnivores, omnivores, scavengers, and detritivores) are referred to
as consumers and those that function through absorption (fungi and bacteria) are referred to as decomposers. The autotrophs that function through photosynthesis are labeled producers.

Figure 2.2: Simplified energy flow and material cycling among Producers, Consumers, and Decomposers

The division of organisms by their means of nutrition can also be shown as an evolutionary family tree, see figure 2.3 below. The kingdom Monera (bacteria) and the kingdom Protista exhibit all three types of nutrition (photosynthesis, absorption, and ingestion). The multicellular organisms of the remaining three kingdoms are more specialized; plants photosynthesize, fungi absorb, and animals ingest (Odum, 1983).
Figure 2.3: A five-kingdom system based on three levels of organization—the prokaryotic (kingdom Monera), eukaryotic unicellular (kingdom Protista), and eukaryotic multicellular and multinucleate. On each level there is divergence in relation to three principal modes of nutrition—the photosynthetic, absorptive, and ingestive: from (Odum, 1983)

Throughout this work, the two division classification of producers and consumers will be used to simplify the study, however, as some points decomposition will be considered separately such as in the anaerobic digestion of egesta.

In addition to the producer-consumer structure displayed by ecosystems, they also display a tendency to move towards a state where producers and consumers are balanced through a process known as succession (Odum, 1983). This state is known as a climax state. A system is in a climax state if GPP equals total respiration (R), in other words, production and consumption are balanced. A system is growing or in a pioneer stage of
autotrophic succession (trees replacing herbaceous plants) if GPP>R, in this case there is more production than consumption and biomass is being generated. A system is either deteriorating or undergoing heterotrophic succession (bacteria multiplying in a sewage pond) when GPP<R, in this case either the consumers are consuming more that the producers are creating, or there is some temporary energy subsidy that allows consumption to proceed at a level that is higher than production (Nierenberg, 1995; Odum, 1983).

In Summary, ecosystems can be seen as stable systems that create and maintain structures made up of cycling materials using energy obtained by the capture, conversion, and degradation of solar energy. A list of fundamental design principles of ecosystems is given below:

- Ecosystems are made up of two main functional groups producers and consumers.

- Producers provide the energy basis for ecosystems through processes of sun driven synthesis.

- Consumers exist by consuming a portion of the energy basis created by producers, but in consuming that energy, release the nutrients necessary for future producer growth.

- Ecosystems move towards a climax state where GPP equals respiration reflecting a balance between production and consumption.

These design principles of ecosystems will be used to help develop a working definition of the term eco-mimetic at the end of this chapter. The next section provides a discussion and overview of the field of industrial ecology.
2.2 An Overview of Industrial Ecology

Industrial ecology (IE) is an emerging field and due to its youth, has no universally accepted definitions. However, several definitions of IE have been put forward. Three selected definitions are given and discussed below. Further discussion of the concepts of IE can be found in Locklear, 2001; Saleem, 2001; and Odom, 2002.

The following definition of IE below was put forth by Robert Frosch (1992):

“The idea of an industrial ecology is based upon a straightforward analogy with natural ecological systems. In nature an ecological system operates through a web of connections in which organisms live and consume each other and each other’s waste. The system has evolved so that the characteristic of communities of living organisms seems to be that nothing that contains available energy or useful material will be lost. There will evolve some organism that will manage to make its living by dealing with any waste product that provides available energy or usable material. Ecologists talk of a food web: an interconnection of uses of both organisms and their wastes. In the industrial context we may think of this as being use of products and waste products. The system structure of a natural ecology and the structure of an industrial system, or an economic system, are extremely similar.”

The following definition of IE was put forth by Brad Allenby (1992):

“somewhat teleologically, ‘industrial ecology’ may be defined as the means by which a state of sustainable development is approached and maintained. It consists of a systems view of human economic activity and its interrelationship with fundamental biological, chemical, and physical systems with the goal of
establishing and maintaining the human species at levels that can be sustained indefinitely, given continued economic, cultural, and technological evolution.”

This last definition was put forth by Hardin Tibbs (1992)

“Industrial ecology involves designing industrial infrastructures as if they were a series of interlocking [hu]manmade ecosystems interfacing with the natural global ecosystem. Industrial ecology takes the pattern of the natural environment as a model for solving environmental problems, creating a new paradigm for the industrial system in the process. The aim of industrial ecology is to interpret and adapt an understanding of the natural system and apply it to the design of the [hu]manmade system, in order to achieve a pattern of industrialization that is not only more efficient, but that is intrinsically adjusted to the tolerance and characteristics of the natural system. The emphasis is on forms of technology that work with natural systems, not against them.”

Frosch states that industrial systems are analogous to ecological systems (ecosystems) and that their system structures are very similar. In seeing industrial systems as analogues to ecosystems, useful parallels or lessons can be drawn. Frosch seems to suggest niche structure and roundput (vs. throughput) as lessons to learn from ecosystems. Allenby views IE as the method or process by which humans can reach and maintain a state of sustainability. Allenby ascribes a systems view or holistic view to IE that clearly shows that humans and human systems are embedded within the biogeochemical systems of the earth. Tibbs sees IE as a means by which natural systems can be used as a model for industrial systems and proposes the view that natural systems should act as a template for redesigning the structure of industrial systems.
Tibb’s idea of human systems imitating ecosystems can be summed up in the term ecomimetic. Some readers may be more familiar with the term biomimicry made popular by Janine Benyus (1997). Biomimetic or life mimicking design normally focuses on a smaller or organismal scale; for example polymers inspired by spider silk or glues inspired by barnacles. Ecomimicry focuses on design at a larger scale, the ecosystem scale. The view of natural systems as a template to create ecomimetic human systems is a stronger interpretation of IE than that proposed by Frosch. Frosch’s view of IE promotes cooperative agreements among existing industries such as waste sharing, but does not call for a redesign of industry.

Two separate philosophies emerge from these definitions. One view sees industrial systems and ecosystems as being very similar in structure. This view proposes that useful lessons can be gained by comparing the two systems. The second view goes beyond seeing similarities in two separate systems and states that the systems are interrelated and linked. This view sees industrial systems as subordinate to natural systems and goes further by requiring that natural systems be the archetypal model on which the design of industrial systems is based.

The definitions point toward a polarized field with two extreme views. We will label one pole of IE as analogy and the other pole as metaphor. The following examples give a summary of where various authors are aligned in the spectrum. In 1989, the same year that the Frosch and Gallopoulos paper was published, Robert Ayres furthered the concept of IE in his journal paper, “Industrial Metabolism and Global Change.” In this paper Ayres compares the metabolism of biotic organisms to that of industrial systems. Ayres argues that there is an analogy between biological and industrial evolution. He
states that the current fossil fuel driven industrial system is at an evolutionary stage equivalent to that of the ancient earth prior to the evolution of anaerobic photosynthesis when the only organisms were fermentation organisms that like our current industrial system are living unsustainably off of “an inherited primordial stockpile of energy-rich compounds.”

Brad Allenby and William Cooper departed from the long-term evolutionary view of Ayres and moved toward shorter time scales by suggesting that the current industrial system resembles a type I succession community (1994). The authors still refer to IE as an analogy, but note that further research in the area is needed. Most significantly, the authors note that industrial systems and biological systems are both “complex systems” and point towards the need for developing “a systems-based, comprehensive intellectual framework.”

Thomas Graedel brought the concept of IE closer to the discipline of ecology by suggesting that the division between the two is “artificial” (because the industrial system is embedded in the ecosystem) and suggesting a new field, earth system ecology (1996). Graedel applies the ecological concept of food webs to industry, creating industrial food webs and suggests that the two fields could benefit from an exchange of ideas and methods. Graedel still describes IE as an analogy, but admits that “little has been done to explore its usefulness.”

In 2000, John Ehrenfeld stated his understanding of the division in the IE community in his journal article, “Industrial Ecology: Paradigm Shift or Normal Science.” Ehrenfeld states that “some authors stress the materials and energy
flows…Others see industrial ecology primarily in its more metaphorical sense as providing new normative themes for a possibly sustainable world.”

Also in 2000, Clinton Andrews refers to IE as metaphor. However, Andrews states that IE “like its counterpart fields of human ecology, cultural ecology, political ecology, and social ecology…is in danger of becoming links between “something” (in this case industry) and the natural environment.”

Lastly, the split between those who see IE at a metaphor and those who see it as an analogy came to the forefront during a technical program titled “Industrial Ecology: The Metaphor” which was held during the International Society for Industrial Ecology inaugural meeting in November of 2001 in the Netherlands. Of the four papers presented, two supported IE as a metaphor, one as an analogy, and one paper attempted to discredit the concept of IE. Much lively discussion on both the metaphor and the analogy side of the debate ensued.

In summary, IE can be seen as a field of study that aspires to develop methodologies that will improve the performance (environmental and otherwise) of technological systems allowing society to reach a state of sustainability. It is proposed that this be done by; using a systems approach, which recognizes technological systems as an embedded part of natural systems and that strives to improve the performance of technological systems by either incrementally changing technological systems using natural systems as an analogy or fundamentally transforming technological systems using natural systems as a metaphor.
2.3 An Overview of Sustainability/Sustainable Development

As is the case for IE, sustainable development (SD) has no universally accepted definition. In order to better understand SD three selected definitions are given below. Other discussions of the concepts of SD can be found in Wallace, 1999; Grigg, 2000; Peterson, 2000; Locklear, 2001; Saleem, 2001; and Odom, 2002.

The following definition was the result of the 1987 publication by the World Commission on Environment and Development that has been dubbed the Bruntland Report and may be the most widely recognized definition of SD:

[Sustainable development is] the ability of humanity to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional changes are made consistent with future as well as present needs.”

This next definition was put forth by David Pearce (1988):

In simple terms [sustainable development] argues for (1) development subject to a set of constraints which set resource harvest rates at levels no higher than managed or natural regeneration rates; and (2) use of the environment as a "waste sink" on the basis that waste disposal rates should not exceed rates of (natural and managed) assimilation by the counter part ecosystems... There are self-evident problems in advocating sustainable rates for exhaustible resources, so that "sustainabilists" tend to think in terms of a resource set encompassing substitution between renewables and exhaustibles. Equally self-evident is the implicit
assumption that sustainability is a "good thing" - that optimizing within sustainable use rates is a desirable objective. On these terms, sustainability could imply use of environmental services over very long time periods and, in theory, indefinitely.

This third and final definition was put forward by the World Conservation Union (1993):

Sustainable development means achieving a quality of life (or standard of living) that can be maintained for many generations because it is:

1. socially desirable, fulfilling people's cultural, material, and spiritual needs in equitable ways;
2. economically viable, paying for itself, with costs not exceeding income;
3. ecologically sustainable, maintaining the long-term viability of supporting ecosystems.

The dominant theme that emerges from these definitions is:

Meeting needs or establishing a quality of life for present and future generations of humans while maintaining healthy social, economic, and ecological systems.

With the review and distillation of the core concepts from biological ecology (BE), IE, and sustainable development (SD); a set of measures must be developed that will allow some quantifiable measurement of the concepts. The next section will address the issue of developing quantifiable measures.

2.4 Synthesizing the Principles of BE, IE, and SD: Creating a Common Language

In order for a meaningful comparison of biotic and anthropic systems to be carried out, a common language needs to be developed. The next section is an attempted beginning of a common language or a language with shared meaning. Definitions were
gathered from literature in biology and ecology. Where possible generalized definitions were crafted that accurately represent the concepts for both biotic and anthropic systems. When generalized definitions did not make sense, specific definitions were developed for anthropic systems and the term is changed to denote the incompatibility. For example, the term net primary productivity (NPP) cannot accurately be generalized for anthropic systems; therefore, the term was changed to anthropic renewable energy subsidy (ARES). The table below contains standard definitions of ecological terms in the left column. The right column contains a definition that has been generalized enough to allow the definition to be applied to industrial systems while still maintaining the original biological meaning. A note to the reader, some of the definitions contain acronyms of terms that are defined later in the table. A glossary of acronyms is provided as a reader’s aid in Appendix A.

Table 2.1: Ecological Definitions and Generalized Equivalent Definitions

<table>
<thead>
<tr>
<th>Ecological/Biotic Definitions</th>
<th>Technological/Anthropic or General Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Climax Community:</strong> the final or stable community in a developmental series, in theory, the climax community is self-perpetuating because it is in equilibrium with itself and with the physical habitat. For Climax Communities GPP/R=1. For autotrophic succession, GPP/R&gt;1, but moving toward unity (example disturbed land transitioning to forest). For heterotrophic succession, GPP/R&lt;1 but moving toward unity (example bacteria in a sewage pond). (Odum, 1983)</td>
<td><strong>Anthropic Climax Community:</strong> a sustainable community where in general, (HANPP+ARES)/(AR)=1</td>
</tr>
<tr>
<td><strong>Net Primary Productivity (NPP):</strong> the amount of energy left after subtracting the respiration of primary producers (mostly plants) from the total amount of energy (mostly solar) that is fixed biologically. NPP provides the basis for maintenance, growth, and reproduction of all heterotrophs (consumers and decomposers); it is the total food resource on Earth. (Vitousek et al, 1986)</td>
<td><strong>Anthropic Renewable Energy Subsidy (ARES):</strong> the renewable energy fixed or assimilated by human systems minus storage and conversion losses, (GARES- losses)</td>
</tr>
</tbody>
</table>
Table 2.1: Ecological Definitions and Generalized Equivalent Definitions- Continued

<table>
<thead>
<tr>
<th><strong>Gross Primary Productivity (GPP):</strong> the total rate of photosynthesis, including the organic matter used up in respiration during the measurement period. This is also known as “total photosynthesis” or “total assimilation.” (Odom, 1983)</th>
<th><strong>Gross Anthropic Renewable Energy Subsidy (GARES):</strong> the total rate of renewable energy fixed or assimilated by human systems (examples solar or wind energy)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net Community Productivity:</strong> the rate of storage of organic matter not used by heterotrophs (that is, net primary production minus heterotrophic consumption) during the period under consideration, usually the growing season or a year. (Odom, 1983)</td>
<td><strong>Net Community Productivity:</strong> the rate of storage of energy not used by heterotrophs (that is, net primary production minus heterotrophic consumption) during the period under consideration.</td>
</tr>
<tr>
<td><strong>Secondary Productivities:</strong> the rates of energy storage at consumer levels. Since consumers use only food materials already produced, with appropriate respiratory losses, and convert to different tissues by one overall process, secondary productivity should not be divided into “gross” and “net” amounts. The total energy flow at heterotrophic levels, which is analogous to gross production of autotrophs, should be designated “assimilation” and not “production.” (Odom, 1983)</td>
<td><strong>Secondary Productivity:</strong> the rates of energy storage at consumer levels. The energy assimilated by heterotrophs minus heterotrophic respiration.</td>
</tr>
<tr>
<td><strong>Consumer:</strong> in the widest sense, a heterotrophic organism that feeds on living or dead organic material. Two main categories are recognized: (a) macroconsumers, mainly animals (herbivores, carnivores, and detrivores), which wholly or partly ingest other living organisms or organic particulate matter; and (b) microconsumers, mainly bacteria and fungi, which feed by breaking down complex organic compounds in dead protoplasm, absorbing some of the decomposition products, and at the same time releasing inorganic and relatively simple organic substances to the environment. Sometimes the term ‘consumer’ is confined to macroconsumers, microconsumers being known as ‘decomposers’. Consumers may then be termed ‘primary’ (herbivores), ‘secondary’ (herbivore-eating carnivores), and so on, according to their position in the food-chain. Macroconsumers are also sometimes termed phagotrophs or biophages, while microconsumers correspondingly are termed saprotrophs or saprophages. (Allaby, 1998)</td>
<td><strong>Consumer:</strong> see Heterotroph</td>
</tr>
<tr>
<td><strong>Decomposer:</strong> a term that is generally synonymous with ‘microconsumer’. In an ecosystem, decomposer organisms (mainly bacteria and fungi) enable nutrient recycling by breaking down the complex organic molecules of dead protoplasm and cell walls into simpler organic and (more importantly) inorganic molecules which may be used again by primary producers. Recent work suggests that some macroconsumers may also play a role in decomposition (for example, detrivores, in breaking down litter, speed its bacterial breakdown). In this sense ‘decomposer’ has a wider meaning than that traditionally implied. (Allaby, 1998)</td>
<td>Example- anaerobic digesters</td>
</tr>
<tr>
<td><strong>Detritivore:</strong> a heterotrophic animal that feeds on dead material (detritus). The dead material is most typically of plant origin, but it may include the dead remains of small animals. Since this material may also be digested by decomposer organisms (fungi and bacteria) and forms the habitat for other organisms (e.g. nematode worms and small insects), these too will form part of the typical detrivore diet. Animals (i.e. the hyena) that feed mainly on the products (exuviae, e.g. dung), of larger animals, are termed scavengers. (Allaby, 1998)</td>
<td>Example- electrical utilities</td>
</tr>
<tr>
<td><strong>Detritus:</strong> litter formed from fragments of dead material (e.g. leaf litter, dung, moulted feathers, and corpses). In aquatic habitats, detritus provides habitats equivalent to those which occur in soil humus. (Allaby, 1998)</td>
<td>Same</td>
</tr>
<tr>
<td><strong>Detrital pathway (detritus food-chain):</strong> most simply, a food-chain in which the living primary producers (green plants) are not consumed by grazing herbivores, but eventually form litter (detritus) on which decomposers (micro-organisms) and detrivores feed, with subsequent energy transfer to various levels of carnivore (e.g. the pathway: leaf litter→earthworm→blackbird→sparrowhawk). Detritus from organisms at higher trophic levels than green plants may also form the basis for a detrital pathway, but the key distinction between this and a grazing pathway lies in the fate of the primary producers. (Allaby, 1998)</td>
<td>Same</td>
</tr>
</tbody>
</table>
Table 2.1: Ecological Definitions and Generalized Equivalent Definitions- Continued

<table>
<thead>
<tr>
<th><strong>Food-chain:</strong> the transfer of energy from the primary producers (green plants) through a series of organisms that eat and are eaten, assuming that each organism feeds on only one other type of organism (e.g. earthworm→blackbird→sparrowhawk). At each stage much energy is lost as heat, a fact that usually limits the number of steps (trophic levels) in the chain to four or five. Two basic types of food-chain are recognized: the grazing and detrital pathways. In practice these interact to give a complex food-web. (Allaby, 1998)</th>
<th>Same</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food-web:</strong> a diagram that represents the feeding relationships of organisms within an ecosystem. It consists of a series of interconnecting food-chains. Only some of the many possible relationships can be shown in such a diagram and it is usual to include only one or two carnivores at the highest levels. (Allaby, 1998)</td>
<td><strong>Food-web:</strong> a diagram that represents the energy exchanges of organisms within an ecosystem. It consists of a series of interconnecting food-chains.</td>
</tr>
<tr>
<td><strong>Herbivore:</strong> a heterotroph that obtains energy be feeding on primary producers, usually green plants. (Allaby, 1998)</td>
<td>Same</td>
</tr>
<tr>
<td><strong>Autotroph:</strong> an organism capable of synthesizing its own food from inorganic substances, using light or chemical energy. (American Heritage Dictionary)</td>
<td><strong>Autotroph:</strong> an organism capable of producing useful energy using inorganic energy sources such as light, chemical, wind, water, wave, geothermal, or nuclear energy (i.e. a producer).</td>
</tr>
<tr>
<td><strong>Heterotroph:</strong> an organism that is unable to manufacture its own food from simple chemical compounds and therefore consumes other organisms, living or dead, as its main or sole source of carbon. Often, single-celled autotrophs (e.g. Euglena) become heterotrophic in the absence of light. (Allaby, 1998)</td>
<td><strong>Heterotroph:</strong> an organism that receives its energy flow from another organism (i.e. a consumer).</td>
</tr>
<tr>
<td><strong>Omnivore:</strong> a heterotroph that feeds on both plants and animals, and thus operates at a range of trophic levels. (Allaby, 1998)</td>
<td><strong>Omnivore:</strong> a heterotroph that feeds on both autotrophs and heterotrophs, and thus operates at a range of trophic levels</td>
</tr>
<tr>
<td><strong>Carnivore:</strong> any heterotrophic, flesh-eating animal. (Allaby, 1998)</td>
<td><strong>Carnivore:</strong> a heterotroph that feeds only on other heterotrophs</td>
</tr>
<tr>
<td><strong>Producer:</strong> in an ecosystem, an organism that is able to manufacture food from simple inorganic substances (i.e. an autotroph, most typically a green plant). (Allaby, 1998)</td>
<td><strong>Producer:</strong> see Autotroph</td>
</tr>
<tr>
<td><strong>Assimilate:</strong> the portion of the food energy consumed by an organism that is metabolized by that organism. Some food, or in the case of a plant some light energy, may pass through the organism without being used. (Allaby, 1998)</td>
<td><strong>Assimilate:</strong> the portion of input energy that an organism metabolizes.</td>
</tr>
<tr>
<td><strong>Ecosystem:</strong> a term first used by A. G. Tansley (in 1953) to describe a discrete unit that consists of living and non-living parts, interacting to form a stable system. Fundamental concepts include the flow of energy via food-chains and food-webs, and the cycling of nutrients biogeochemically. Ecosystem principles can be applied at all scales. Principles that apply to an ephemeral pond, for example, apply equally to a lake, an ocean, or the whole planet. In Soviet and central European literature ‘biogeocoenosis’ describes the same concept. (Allaby, 1998)</td>
<td><strong>Anthropic System or Technosystem:</strong> a discrete human created system, consisting of producers and consumers. For example a country, state, or city</td>
</tr>
<tr>
<td><strong>Grazing Pathway (grazing food-chain):</strong> a food-chain in which the primary producers (green plants) are eaten by grazing herbivores, with subsequent energy transfer to various levels of carnivore (e.g. plant (blackberry, <em>Rubus</em>) → herbivore (bank vole, <em>Clethrionomys glareolus</em>) → carnivore (tawny owl, <em>Strix aluco</em>). (Allaby, 1998)</td>
<td>Same</td>
</tr>
<tr>
<td><strong>Metabolism:</strong> the total of all the chemical reactions that occur within a living organism (e.g. those involved in the digestion of food and the synthesis of compounds from metabolites so obtained). (Allaby, 1998)</td>
<td>Same</td>
</tr>
<tr>
<td><strong>Respiration:</strong> oxidative reactions in cellular metabolism that involve the sequential degradation of food substances and the generation of a high-energy compound, ATP (adenosine triphosphate) in aerobic respiration with the use of molecular oxygen as a final hydrogen acceptor; ATP, carbon dioxide, and water are the products thus formed. (Allaby, 1998)</td>
<td><strong>Respiration:</strong> the expenditure of assimilated energy to do work</td>
</tr>
<tr>
<td><strong>Respiration-biomass ratio (R/B ratio):</strong> the relationship between total community biomass (i.e. standing crop) and respiration. With larger biomass, respiration will increase but the increase will be less if the individual biomass units or organisms are large (reflecting the inverse relationship between size and metabolic rate). Natural communities tend toward larger organisms and complex structure, with low respiration rates per unit biomass. (Allaby, 1998)</td>
<td>Total energy expenditure divided by the biomass of the human population. NA due to the biomass energy disconnect in Technosystems-- -- but could divide total respiration by the biomass of humans which the energy flow ultimately serves******</td>
</tr>
<tr>
<td>Metastable System: <strong>a physical, chemical, or biological system that has temporarily stabilized at a higher than normal energy level, usually due to some outside inducement.</strong> A metastable system may be anything from an atom in which one or more electrons have skipped up to higher level shells to an ecosystem such as a grassland in which the species composition has been changed by intense grazing pressure. Metastable systems are always in danger of collapse. (Ashworth, 1991)</td>
<td>Same</td>
</tr>
<tr>
<td><strong>Biome:</strong> a biological subdivision that reflects the ecological and physiognomic character of the vegetation. Biomes are the largest geographical biotic communities that it is convenient to recognize. They broadly correspond with climatic regions, although other environmental controls are sometimes important. They are equivalent to the concept of major plant formations in plant ecology, but are defined in terms of all living organisms and of their interaction with the environment (and not only with the dominant vegetation type). Typically, distinctive biomes are recognized for all the major climatic regions of the world, emphasizing the adaptation of living organisms to their environment, e.g. tropical rain-forest biome, desert biome, tundra biome. (Allaby, 1998)</td>
<td><strong>Technome:</strong> an area of the technosphere delineated by the type of technological organism that dominates. Candidates: urban, suburban, commercial, industrial, agricultural, and recreational technomes</td>
</tr>
<tr>
<td><strong>Biosphere:</strong> the part of the Earth’s environment in which living organisms are found, and with which they interact to produce a steady-state system, effectively a whole-planet ecosystem. Sometimes it is termed ‘ecosphere’ to emphasize the interconnection of the living and non-living components. (Allaby, 1998)</td>
<td><strong>Anthroposphere or Technosphere:</strong> a subset of the biosphere that includes humans and their creations</td>
</tr>
<tr>
<td>Energy Subsidy: besides solar energy, an ecosystem may also be supported by external sources of energy that lessen its internal self-maintenance. This is called energy subsidy or auxiliary energy and is responsible for higher outputs (productivity) of an ecosystem. (Nierenberg, 1995)</td>
<td>Technical Energy Subsidy: any energy other than HANPP &amp; NTP that maintains the technosystem at an elevated energy/metastable state.</td>
</tr>
<tr>
<td>Human Appropriation of Net Primary Productivity (HANPP): can be defined as a geographic area’s potential NPP which is “used directly, co-opted, or forgone because of human activities” (Vitousek et al, 1986).</td>
<td>Same</td>
</tr>
</tbody>
</table>

2.4 Synthesizing the Principles of BE, IE, and SD: Creating Metrics

Energy flow assessment or accounting (EFA) is a tool that can be used to map energy flows through biological and technological systems. EFA is a complementary procedure to materials flow accounting (MFA). Both EFA and MFA are methods that attempt to define the metabolism of a given system. This concept of energetic or material metabolism of technological systems can be broadly classified as socioeconomic metabolism (Krausmann and Haberl, 2002). Socioeconomic metabolism or industrial metabolism is based on the biological concept and was developed by Robert Ayres (1989). More detailed discussions of EFA, MFA, and industrial metabolism can be found in the following works (Krausmann and Haberl, 2002; Fischer-Kowalski and Haberl, 1997; Kowalski, 1998; Kowalski, 1999; Haberl, 2001 I; Haberl, 2001 II).

Fundamentally EFA is a first law or input-output study of energy flows. Digraphs can be used to represent the energy flows of the EFA. The digraph nodes represent processes or significant quantities of energy and the edges represent energy flows. The symbol for electrical ground represents the dissipation of energy into a lower quality
unusable form. Figure 2.4 below is a digraph of energy flow through a natural system.

This is fundamentally the same diagram as figure 2.1 in the previous section.

![Figure 2.4: Digraph of Energy flow Through an Ecosystem](image)

In the figure above a producer takes in sunlight. Some of the sunlight is fixed through photosynthesis, this fixed sunlight is considered GPP. Some of the GPP is lost due to producer respiration and the remainder is considered NPP. Consumers use the NPP to drive their metabolism which ultimately ends up as respiration. Note that there is no cycling in this digraph because energy is the only flow being considered; only materials cycle in ecosystems, the energy is dissipated. Also included are imports and exports of biomass across the system boundary. Immigration and emigration is the movement of consumer organisms across the system boundary.
The figure above does not consider the human system separately from the natural system. One of the measures that can be used to separate the human and natural systems and determine human impact on a given area is termed human appropriation of net primary productivity (HANPP) (Haberl, 2001 I). HANPP can be defined as a geographic area’s potential NPP which is “used directly, co-opted, or forgone because of human activities” (Vitousek et al, 1986). NPP is forgone when an area is modified from its natural state to a lower energy state for example when a productive forest is cut to build a parking lot which has a lower NPP. An example of direct use of NPP is food for human consumption and an example of co-opted NPP is fodder for livestock. It should be noted that if an area was modified and became more productive (growing crops in a desert area) the forgone NPP would be negative and would result in a net reduction of heating.

Figure 2.5 below relates the concept of HANPP to system energy flows. This is an adaptation of figure 2.4 above which shows the flows through the anthroposphere separately from the biotic flows. In general, any abbreviation that begins with an “A” denotes anthropic flows and those that begin with a “B” denote biotic flows.
Figure 2.5: Digraph of Energy Flows in the Biotic/Anthropic System

In the figure above, potential NPP (PNPP) represents an ecosystem’s potential productivity. PNPP is a virtual measure of how productive an ecosystem would be in an undisturbed state. The total NPP (TNPP) is a real measure of how productive the ecosystem is at the time of measurement. TNPP is divided between the ecosystem which supports itself with the remaining NPP (RNPP) and the human system which supports itself with the HANPP. Some portion of the HANPP is made up of the virtual forgone NPP (FNPP), which is not available to support the anthroposphere and is represented as respired or lost energy in the diagram.

There is no defined amount of HANPP which delineates too much or an unsustainable amount of human consumption (other than HANPP ≥ PNPP). However, as HANPP increases the remaining NPP (RNPP) or the amount of energy left to support ecosystem structure and function decreases. Even thought there is no set limit for HANPP, an attempt has been made to identify the difference between sustainable and
unsustainable trends. Day et al have defined an area to be ecologically sustainable if the change in net primary productivity (in this case TNPP) remains greater than or equal to zero over extended time spans (1997). Cardoch et al point out that this definition is not sufficient due to the effects increasing HANPP can have on the system (2002). They have defined a river delta as “ecologically sustainable when RNPP is nondeclining and HANPP is nonincreasing relative to TNPP” (Cardoch et al, 2002). This definition of ecological sustainability allows for the inclusion of human impacts. In summary, HANPP indicates the interaction between biotic and anthropic systems. HANPP can be used as an indicator of how much stress human systems are causing natural systems and as a potential indicator of ecological sustainability given the availability of data over time.

Social sustainability can be summarized from the definitions above as establishing a quality of life that is socially desirable fulfilling material, cultural, and spiritual needs. This list of needs closely represents Maslow’s hierarchy of needs which includes physiological, safety, love, esteem, and self-actualization (Maslow, 1970). In an effort to create some metrics that would define social sustainability in terms of energy flow, physiological needs are considered first order constraints and all others second order constraints. After meeting physiological needs, any surplus energy will be divided equally among the population. As social sustainability is very complicated subject containing many dimensions not represented by energy flows, this study will only attempt to review energy needs for physiological requirements and will not presume to be able to make determinations of social sustainability.
Economic sustainability can be summarized from the definitions above as establishing a quality of life that is economically viable, paying for itself, with costs not exceeding income. Because this study involves isolating South Carolina and viewing only energy flows, it will be difficult to determine if the system is economically sustainable. Economic sustainability is treated as a second order constraint. Therefore, this study will not presume to be able to make a determination of economic sustainability.

Another measure that can be used to define system’s state is the system stability or state of succession. A system is stable or in climax state if GPP equals total respiration (R), a system is growing or in a pioneer stage of autotrophic succession (trees replacing herbaceous plants) if GPP>R, and a system is either deteriorating or undergoing heterotrophic succession (bacteria multiplying in a sewage pond) when GPP<R (Nierenberg, 1995; Odum, 1983). Stability can apply to the anthroposphere as well. For the anthroposphere to be stable or in climax, the anthropic nonrenewable energy subsidy (ANRES) must be zero and the system inputs must equal the system outputs. Therefore, the sum of HANPP, ARES, and AI must be equal to the sum of the AW, AR, and AE. If the ANRES is non-zero, then the system is at some level of metastability. Metastability implies that some transient external energy source is supporting the system at an elevated energy level. According to Ashworth, a metastable system is a “physical, chemical, or biological system that has temporarily stabilized at a higher than normal energy level, usually due to some outside inducement. A metastable system may be anything from an atom in which one or more electrons have skipped up to higher level shells to an ecosystem such as a grassland in which the species composition has been changed by intense grazing pressure. Metastable systems are always in danger of collapse”
(Ashworth, 1991). In the case of the biosphere, if FNPP is increasing (i.e. productive land is being converted into less productive areas) then the system is in decline, because there are assumed to be no subsidies supporting the biosphere. For the anthroposphere, if there is a transient energy subsidy, then the system is metastable. The degree of metastability can be defined as the ratio of the ANRES to the sum of HANPP and ARES. Increasing the ARES keeps the human system at an elevated energy level, but because the subsidy is renewable, the system is not in danger of collapse. However, the anthropic system’s overall stability is dependant upon the stability of the biotic system because it is a subsystem of the biotic system.

In summary, the initiating purpose for this review of literature was to gain a general understanding of BE, IE, and SD and then to use that understanding to develop a distillation of the fundamental architecture of the energy flows in natural systems and a quantifiable definition of what is sustainable. In order to use a natural system as a template or create what can be called an eco-mimetic system, a system that mimics an ecosystem, the following design principles must apply:

The energy basis for eco-mimetic systems must be provided by sun driven processes (ANRES=0);

Eco-mimetic systems must move towards a climax state where energy inputs (HANPP+ARES+AI) equal energy outputs (AR+AW+AE) reflecting a balance between production and consumption.

In order for an anthropic system to be sustainable it must meet the following criteria:

Ecological Sustainability: maintaining the long-term viability of supporting ecosystems, RNPP is nondeclining and HANPP is nonincreasing relative to TNPP;

Social Sustainability: socially desirable, fulfilling people's cultural, material, and spiritual needs in equitable ways, using Maslow’s hierarchy of needs physiological needs must be met. However, higher order needs will not be
examined in this study;

Economic Sustainability: economically viable, paying for itself, with costs not exceeding income. Economic sustainability is treated as a second order constraint and will not be examined in this study.

The main focus of this work will be ecological sustainability and meeting the physiological needs of the population, therefore, determinations of social and economic sustainability will not be made.
CHAPTER THREE

METHODOLOGY

3.1 Boundaries

Temporal boundaries of the study are set based on the history of South Carolina and availability of data. The initial boundary is set by the recession of the last ice age and the subsequent establishment of a climax forest community is South Carolina about 8000 years ago (Adams and Faure, 2003). The final boundary is set at the end of the year 2000 due to lack of data for more recent years. This 10,000 year span was divided into three ages based on the history of South Carolina. The first is termed the pristine age lasting from 6000BC to 1600. The second is the agricultural age beginning in 1600 and ending in 1900. The third is the industrial age beginning in 1900 and continuing through the present.

Spatial boundaries remain fixed throughout the study as the modern geopolitical borders of South Carolina. The coastal border of the state includes an amount of the coastal waters which extends about 5,500 meters beyond the land.

3.2 Tools and Data

Geographic information system (GIS), spreadsheet, database, and word-processing software were used throughout the study as required by the data sets. Detailed discussions of GIS and its uses can be found in other works (Wallace, 1999; Grigg, 2000;
Locklear, 2001). Major data sets included the 2000 US census (US Census, 2003), satellite image files of South Carolina land cover which are referred to as SPOT data (USC GIS, 2003), the 2002-2003 South Carolina Industrial Directory (SCID, 2003), the Department of Energy’s Energy Information Administration (DOE EIA, 2003) State level energy consumption data, and DOE EIA Manufacturing Energy Consumption Survey data (MECS, 2003). Unless otherwise noted, the references above are the source of all of the data used in this study.

In order to model the energy flows in South Carolina over time, a baseline dataset is needed that can be used for temporal extrapolations. In natural systems, the energy flows depend on the biome type and its area. The image in figure 3.1 below is a graphic representation of land use in South Carolina compiled from the SPOT data which was gathered from satellite imagery using the Systeme Pour l'Observation de la Terre (SPOT).

![Land Use in South Carolina Compiled from 1990 SPOT Data](image_url)

Figure 3.1: Land Use in South Carolina Compiled from 1990 SPOT Data
While there is some concern about the accuracy of land use/land cover classification using SPOT imagery; this datalayer represents the most current land use/land cover that has been assembled for the entire state of South Carolina (Porter, 2003). In an effort to verify the accuracy of the SPOT data, some other estimates of land cover have been assembled from various sources for comparison. The data has been assembled in table 3.1 below.

<table>
<thead>
<tr>
<th>Land Types</th>
<th>SPOT Data</th>
<th>Dahl,1999</th>
<th>Conner and Sheffield, 2000</th>
<th>Graham and Pavlasek, 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (m²)</td>
<td>Area Percentages</td>
<td>Area (m²)</td>
<td>Area Percentages</td>
</tr>
<tr>
<td>Forest</td>
<td>40,834,069,840</td>
<td>51.2%</td>
<td>38,311,874,761</td>
<td>49.0%</td>
</tr>
<tr>
<td>Agricultural/ Grassland</td>
<td>13,227,792,217</td>
<td>16.6%</td>
<td>13,291,874,917</td>
<td>17.0%</td>
</tr>
<tr>
<td>Scrub/Shrub</td>
<td>9,997,936,280</td>
<td>12.5%</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Swamp/Bottomland Forest</td>
<td>7,238,164,235</td>
<td>9.1%</td>
<td>11,728,124,927</td>
<td>15.0%</td>
</tr>
<tr>
<td>Water</td>
<td>2,343,357,539</td>
<td>2.9%</td>
<td>2,345,624,985</td>
<td>3.0%</td>
</tr>
<tr>
<td>Urban/Built Up</td>
<td>3,867,627,041</td>
<td>4.8%</td>
<td>5,473,124,466</td>
<td>7.0%</td>
</tr>
<tr>
<td>Marsh/Estuarine</td>
<td>1,963,483,657</td>
<td>2.5%</td>
<td>1,806,131,239</td>
<td>2.3%</td>
</tr>
<tr>
<td>Other Wetlands</td>
<td>324,806,625</td>
<td>0.4%</td>
<td>3,127,499,981</td>
<td>4.0%</td>
</tr>
</tbody>
</table>

Total State Land Area: 79,797,237,424 78,187,499,513

Table 3.1: Comparison of Land areas from Various Sources

All of the land cover percentages agree well with a few exceptions. Dahl’s wetland forest area estimation (15 percent) is larger than the SPOT data (9.1 percent) and the SC Forest Resources data (10.6 percent listed as oak-gum-cypress forest) (Conner and Sheffield, 2000). Dahl has no category for scrub/shrub land cover which is a significant area (12.5 percent) in the SPOT data. The SPOT data has no category for other wetlands which is a significant area (4 percent) in Dahl’s data. Graham and Pavlasek show a much larger area of farm land than the other estimates, but assuming that many farms probably contain large tracts of forest, the difference may not be significant (2002).

If the Shrub/Scrub area in the SPOT data was divided among the bottomland forest, urban, and other wetlands categories then there would be a stronger correlation between the Spot data and Dahl’s data. Because data are similar in most categories and due the fact that the SPOT data is the only comprehensive data set available for South
Carolina, the SPOT data will be used throughout the rest of this paper. The reader should be advised that the area of forested wetlands currently existing may be underestimated; however, if the SPOT data are more accurate then the state’s wetlands are in more danger than current studies imply.

3.3 Metrics

In general, all distances are measured in meters and the standard energy unit is the kilogram calorie or kcal. Energy values are calculated in terms of calorific values, thus any substance that is combustible will be considered in the analysis. Also included, though not combustible, is electromagnetic energy both sunlight and electrical energy. Energy flows are considered on an annual basis. This works well for biological and technological systems because both vary with seasonal fluctuations. Using an annual time scale division smoothes out the fluctuations in both systems and allows for a uniform analysis. Energy flow analysis or accounting (EFA) will be used to map energy flows through biological and technological systems and digraphs will be used to represent the energy flows in graphic form. HANPP will be used to determine human impact on a given area.

3.4 Methods and Models

An EFA will be carried out for each of the defined time periods using the defined spatial boundary. Metrics will be calculated for each period. An ecomimetic model will be created based on current energy flows and population levels in the system and evaluated for sustainability. This model is referred to as the status quo climax model. If the status quo climax model does not meet the conditions for sustainability as discussed
in the previous chapter, per capita energy flows will be reduced within reason to see if the system can be made sustainable.

In general terms, the models developed in this study models can be considered state space models because they determine the state (sustainable or unsustainable) of the system in question. These models are not strict mathematical models due to a lack of detailed information. The information available determines how the system of study will be abstracted. Natural system modeling is based on biome type and area using an average value of NPP for that biome type with no feedback describing actual biome health or functioning. Human system modeling during the pristine and agricultural age is based on population figures and estimates of individual metabolism. During the industrial age, human system internal metabolism is based on population; however, external metabolism data is based on energy consumption data. Due to these variations in data availability, no general governing equations are developed. However, the available information and concomitant assumptions allows for the state of each system to be determined and provides a model structure that can be used for the evaluation of various scenarios.
CHAPTER 4

MODELING PAST AND PRESENT ENERGY FLOWS

The ways of God in Nature, as in Providence, are not as our ways; nor are
the models that we frame any way commensurate to the vastness,
profundity, and unsearchableness of His works, which have a depth in
them greater than the well of Democritus.

Joseph Glanvill

4.1 South Carolina Energetics: Pristine Age 6000BC to 1600

From about 22,000 to 13,500 years ago during the peak of the last ice age the land
cover of the area that is now South Carolina was a patchwork of open pine-dominated
forest and prairie grassland (Adams and Faure, 2003). During this period around 15,000
years ago the first humans, nomadic hunters, entered the state (Edgar, 1998). Pollen data
shows that by 8,000 years ago South Carolina had changed from open pine forest and
grassland to a heavily forested landscape with oaks contributing about forty percent of
the total pollen influx (Adams and Faure, 2003). This time period, from 8,000 years ago
until the first permanent colonization of Europeans 400 years ago, will be the first period
of energy flow examination in this study.
During the “Pristine Age” of South Carolina, the landscape would have been different from its current state. The current man-made lakes would have been bottomland forest (swamp) or deciduous forest. The current urban, barren, shrub/scrub, and agricultural areas would have been evergreen, deciduous, or mixed forest. In order to determine the energetics of South Carolina during this time period an approximation of the past landscape must be constructed. Table 4.1 below describes the current land cover and associated rates of net primary productivity (NPP). It should be noted that this data includes coastal waters to more accurately calculate aquatic NPP for the state and therefore has a larger area of water than that category in table 3.1 in the previous chapter.

The estimates of NPP for the different biome types are taken from Bolin et al (1979).

<table>
<thead>
<tr>
<th>Land Types</th>
<th>Land Areas (m²)</th>
<th>Area Percentages</th>
<th>NPP Rates (kcal/m² yr)</th>
<th>Total NPP (kcal/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evergreen Forest</td>
<td>2.10E+10</td>
<td>25.3%</td>
<td>7500</td>
<td>1.573E+14</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>1.76E+10</td>
<td>21.3%</td>
<td>6500</td>
<td>1.145E+14</td>
</tr>
<tr>
<td>Agricultural/ Grassland</td>
<td>1.32E+10</td>
<td>16.0%</td>
<td>3040</td>
<td>4.021E+13</td>
</tr>
<tr>
<td>Scrub/Shrub</td>
<td>1.00E+10</td>
<td>12.1%</td>
<td>4000</td>
<td>3.999E+13</td>
</tr>
<tr>
<td>Swamp/Bottomland Forest</td>
<td>7.24E+09</td>
<td>8.7%</td>
<td>12500</td>
<td>9.048E+13</td>
</tr>
<tr>
<td>Water</td>
<td>5.43E+09</td>
<td>6.5%</td>
<td>2000</td>
<td>1.086E+13</td>
</tr>
<tr>
<td>Urban/Built Up</td>
<td>3.87E+09</td>
<td>4.7%</td>
<td>2500</td>
<td>9.669E+12</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>2.24E+09</td>
<td>2.7%</td>
<td>6500</td>
<td>1.459E+13</td>
</tr>
<tr>
<td>Marsh</td>
<td>1.96E+09</td>
<td>2.4%</td>
<td>12500</td>
<td>2.454E+13</td>
</tr>
<tr>
<td>Barren</td>
<td>3.25E+08</td>
<td>0.4%</td>
<td>2500</td>
<td>8.120E+11</td>
</tr>
<tr>
<td><strong>Totals:</strong></td>
<td><strong>8.29E+10</strong></td>
<td></td>
<td><strong>5.030E+14</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Current South Carolina Land Cover and NPP (1989 SPOT Satellite Imagery)

One of the major changes to SC’s geography has been the conversion of wetlands into agricultural, silvicultural, and urban lands (Dahl, 1999). Although it is not possible to exactly determine the extent of past wetlands, one source estimates that there were up to 26 billion square meters of wetlands (including estuarine or marsh areas) in South Carolina in the 1700’s (Dahl, 1990). Because the majority of wetland conversion took place in freshwater wetlands, excluding saltwater marshes which were converted to rice fields but have since reverted to marsh, it can be assumed that of the 26 billion square
meters of total pristine time period wetlands, 2 billion square meters was marsh and 24 billion square meters was bottomland forest or swamp (Dahl, 1999).

Another land cover change was the addition of the major man-made water bodies in the state including lakes Jocasse, Kewowee, and Hartwell in Oconee, Pickens, and Anderson counties; lakes Russell and Thurmond in Abbeville, McCormick, and Edgefield counties; Lake Murray assumed to be mainly in Lexington and Richland counties; Lake Wylie in York County; Lake Greenwood assumed to be located mainly in Greenwood County; Lake Wateree assumed to be located mainly in Kershaw County; and lakes Marion and Moultrie assumed to be mainly located in Clarendon and Berkeley counties (Dahl, 1999). Taken together, these lakes cover approximately 1.39 billion square meters (SCIWAY, 2003)

The remainder of the land cover types to be addressed include agricultural/grassland, scrub/shrub, urban/built up, and barren. The total combined areas of these land types including the area covered by man-made lakes is approximately 29 billion square meters. Taking away the area of converted wetlands and assuming that the remaining land area was covered by the same ratio of evergreen forest to deciduous forest as currently exists (1.19 to 1), a reconstruction of South Carolina’s land coverage can be estimated. Table 4.2 below is an estimate of the areas of land types and associated NPPs for SC during the pristine age.
## Table 4.2: Estimate of South Carolina Land Cover and NPP for Pristine Age (13,000 BC)

<table>
<thead>
<tr>
<th>Land Types</th>
<th>Land Areas (m^2)</th>
<th>Area Percentages</th>
<th>NPP Rates (kcal/m^2 yr)</th>
<th>Total NPP (kcal/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evergreen Forest</td>
<td>2.75E+10</td>
<td>33.2%</td>
<td>7500</td>
<td>2.064E+14</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>2.31E+10</td>
<td>27.9%</td>
<td>6500</td>
<td>1.503E+14</td>
</tr>
<tr>
<td>Swamp/Bottomland Forest</td>
<td>2.40E+10</td>
<td>29.0%</td>
<td>12500</td>
<td>3.000E+14</td>
</tr>
<tr>
<td>Water</td>
<td>4.04E+09</td>
<td>4.9%</td>
<td>2000</td>
<td>8.084E+12</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>2.24E+09</td>
<td>2.7%</td>
<td>6500</td>
<td>1.459E+13</td>
</tr>
<tr>
<td>Marsh</td>
<td>1.96E+09</td>
<td>2.4%</td>
<td>12500</td>
<td>2.454E+13</td>
</tr>
<tr>
<td>Totals:</td>
<td>8.29E+10</td>
<td></td>
<td></td>
<td>7.040E+14</td>
</tr>
</tbody>
</table>

During the pristine age of SC, aboriginal tribes totaling around 30,000 people populated the state (Edgar, 1998). After European contact in 1521, aboriginal population plunged from its peak to about 14,000 by the year 1600 (Swanton, 1979). We will focus on the peak population period prior to 1521.

We will assume that the pristine landscape was not significantly modified (e.g. minimal land clearing and gardening) by these 30,000 residents and that their only impact was the consumption of NPP. It is not possible to know exact values of aboriginal biomass consumption. However, it has been estimated that hunter-gatherers in general consume per person per day 2390 kcal of food, 2390 kcal of plant material for fiber and tools, and 2390 kcal of wood for fires (Haberl, 2001 II). This yields an annual per capita biomass consumption of 2.62 million kcal or a HANPP of 78.5 billion kcal for the entire population, which is about 0.01 percent of the state’s total annual NPP.

Forest dwelling herbivores on average consume about 5 percent of the total NPP (Bolin et al, 1979), therefore, herbivore consumption for the state would have been about 35 trillion kcal or about 448 times greater than human consumption of NPP. During the pristine age, man existed in South Carolina as just another heterotroph. Figure 4.1 below graphically depicts the energy flows in South Carolina during the pristine period.
The energy flows in figure 4.1 were calculated using the following assumptions. It was assumed that of the food energy 20 percent was egested and 80 percent was assimilated and respired (Ricklefs, 1983). All of the plant material for fiber and tools was assumed to flow as waste back to the ecosystem and all of the firewood was assumed to be burned and therefore respired.

Figure 4.1: Digraph of Energy Flows in the Pristine Biotic/Anthropic System

The pristine age anthroposphere was ecomimetic because it used only energy from sun driven processes (ANRES=0) and it was in a climax state (inputs equal to outputs). The pristine age anthroposphere was also most likely sustainable, as the system had sustained itself for the preceding seven thousand years. See table 4.3 below for a summary of relevant metrics.
<table>
<thead>
<tr>
<th>Metric (all metrics in kcal)</th>
<th>Pristine Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANRES</td>
<td>0</td>
</tr>
<tr>
<td>Inputs</td>
<td>7.85E10</td>
</tr>
<tr>
<td>(HANPP-FNPP+ARES+AI)</td>
<td></td>
</tr>
<tr>
<td>Outputs (AR+AW+AE)</td>
<td>7.85E10</td>
</tr>
<tr>
<td>TNPP</td>
<td>7.04E14</td>
</tr>
<tr>
<td>RNPP</td>
<td>7.04E14</td>
</tr>
<tr>
<td>HANPP</td>
<td>7.85E10</td>
</tr>
<tr>
<td>RNPP/TNPP</td>
<td>99.99%</td>
</tr>
<tr>
<td>HANPP/TNPP</td>
<td>0.01%</td>
</tr>
<tr>
<td>Ecological Sustainability</td>
<td>Sustainable?</td>
</tr>
</tbody>
</table>

Table 4.3 Summary of key metrics Pristine Age

### 4.2 South Carolina Energetics: Agricultural Age from 1600-1900

As colonists arrived from Europe the aboriginal people and their way of life was rapidly extinguished and replaced by a burgeoning colonial population and their agrarian way of life. The agrarian lifestyle requires farmland, and the pristine land cover of South Carolina was modified to meet this requirement. Pine tar and pitch were large exports totaling over 52,000 barrels per year in 1719 (Edgar, 1998). Labor intensive rice and indigo were also grown and exported with rice exports reaching thirty million pounds per year in the early 1740s (Edgar, 1998). Rice growing in South Carolina took place largely in tidal marshlands and production reached about 160 million pounds in the 1850s (Dahl, 1999). Unsubsidized rice paddies yield about 0.319 pounds per square meter (Odum, 1983). Rice farmers in South Carolina would have converted about 502 million square meters or over twenty five percent of existing tidal marsh into rice fields by the 1850s. Harvested rice energy content is about 3.5 kcal per gram (Odum, 1983). The total harvest in the 1850s represents about 254 billion kcal in terms of energy.
Due to a lack of information about biomass exports and land conversions a conservative method was used to estimate the amount of forest land converted to other than rice agriculture. This method estimates the amount of land converted to farmland by calculating the amount of farmland required to produce the agricultural energy required by the population (15.4 million kcal of food and fodder per person per year). This figure is based on food consumption of 872 thousand kcal per person per year and a new energy flow of animal fodder was introduced at a flow rate of 14.5 million kcal per person per year; also included in the analysis, but not in the agricultural land total is firewood use of 3.5 million kcal per person per year (Fischer-Kowalski and Haberl, 1997). Unsubsidized wheat farming has a NPP of 1,380 kcal per square meter per year (Odum, 1983). The energy value for wheat farming will be used as an average value for agriculture during the agricultural age. Table 4.4 below shows colonial population their energy use and land conversion to agriculture

It should be noted that slave populations from 1700 till 1860 were over half of the total colonial population. There may have been large discrepancies between free and slave energy use, however, we assume that on average no differences existed. We also assume that the aboriginal population does not play a significant part in the energetics of the state during the agricultural age. It is also assumed that one half of the NPP produced by the agricultural land is lost due to spoilage and herbivory (Vitousek et al, 1986).
<table>
<thead>
<tr>
<th>Year</th>
<th>Total Population</th>
<th>Total Energy Use/ HANPP (kcal/year)</th>
<th>Agricultural Energy (kcal/year)</th>
<th>Land Area Needed for Agriculture (m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1670</td>
<td>155</td>
<td>2.925E+09</td>
<td>2.387E+09</td>
<td>3.46E+06</td>
</tr>
<tr>
<td>1680</td>
<td>1,200</td>
<td>2.265E+10</td>
<td>1.848E+10</td>
<td>2.68E+07</td>
</tr>
<tr>
<td>1700</td>
<td>5,500</td>
<td>1.038E+11</td>
<td>8.470E+10</td>
<td>1.23E+08</td>
</tr>
<tr>
<td>1708</td>
<td>9,580</td>
<td>1.808E+11</td>
<td>1.475E+11</td>
<td>2.14E+08</td>
</tr>
<tr>
<td>1720</td>
<td>18,500</td>
<td>3.491E+11</td>
<td>2.849E+11</td>
<td>4.13E+08</td>
</tr>
<tr>
<td>1730</td>
<td>30,000</td>
<td>5.662E+11</td>
<td>4.620E+11</td>
<td>6.70E+08</td>
</tr>
<tr>
<td>1740</td>
<td>60,000</td>
<td>1.132E+12</td>
<td>9.240E+11</td>
<td>1.34E+09</td>
</tr>
<tr>
<td>1750</td>
<td>65,000</td>
<td>1.227E+12</td>
<td>1.001E+12</td>
<td>1.45E+09</td>
</tr>
<tr>
<td>1760</td>
<td>84,000</td>
<td>1.585E+12</td>
<td>1.294E+12</td>
<td>1.87E+09</td>
</tr>
<tr>
<td>1770</td>
<td>130,000</td>
<td>2.453E+12</td>
<td>2.002E+12</td>
<td>2.90E+09</td>
</tr>
<tr>
<td>1780</td>
<td>180,000</td>
<td>3.397E+12</td>
<td>2.772E+12</td>
<td>4.02E+09</td>
</tr>
<tr>
<td>1790</td>
<td>249,073</td>
<td>4.701E+12</td>
<td>3.836E+12</td>
<td>5.56E+09</td>
</tr>
<tr>
<td>1800</td>
<td>345,591</td>
<td>6.522E+12</td>
<td>5.322E+12</td>
<td>7.71E+09</td>
</tr>
<tr>
<td>1810</td>
<td>415,115</td>
<td>7.834E+12</td>
<td>6.393E+12</td>
<td>9.26E+09</td>
</tr>
<tr>
<td>1820</td>
<td>490,309</td>
<td>9.253E+12</td>
<td>7.551E+12</td>
<td>1.09E+10</td>
</tr>
<tr>
<td>1830</td>
<td>581,185</td>
<td>1.097E+13</td>
<td>8.950E+12</td>
<td>1.30E+10</td>
</tr>
<tr>
<td>1840</td>
<td>594,398</td>
<td>1.122E+13</td>
<td>9.154E+12</td>
<td>1.33E+10</td>
</tr>
<tr>
<td>1850</td>
<td>668,507</td>
<td>1.262E+13</td>
<td>1.030E+13</td>
<td>1.49E+10</td>
</tr>
<tr>
<td>1860</td>
<td>703,708</td>
<td>1.328E+13</td>
<td>1.084E+13</td>
<td>1.57E+10</td>
</tr>
<tr>
<td>1870</td>
<td>705,606</td>
<td>1.332E+13</td>
<td>1.087E+13</td>
<td>1.57E+10</td>
</tr>
<tr>
<td>1880</td>
<td>995,577</td>
<td>1.879E+13</td>
<td>1.533E+13</td>
<td>2.22E+10</td>
</tr>
<tr>
<td>1890</td>
<td>1,151,149</td>
<td>2.172E+13</td>
<td>1.773E+13</td>
<td>2.57E+10</td>
</tr>
<tr>
<td>1900</td>
<td>1,340,316</td>
<td>2.529E+13</td>
<td>2.064E+13</td>
<td>2.99E+10</td>
</tr>
</tbody>
</table>

Table 4.4: Conversion of Land for Agricultural Use: data from (Rogers and Taylor, 1994; UVA Geospatial and Statistical Data Center, 1998)

The area land converted to non rice agricultural purposes grew from zero in the year 1600 to almost 30 billion square meters by 1900, which is more than twice the amount currently classified as agricultural land. No data on urban land area is available for this period. We will assume that most residents lived on farms, thus the urban area would be included in the agricultural area.

Table 4.5 below lists the land cover and net primary productivity of South Carolina during the peak of the agricultural age.
<table>
<thead>
<tr>
<th>Land Types</th>
<th>Land Areas (m²)</th>
<th>Area Percentages</th>
<th>NPP Rates (kcal/m²² yr)</th>
<th>Total NPP (kcal/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upland Forest</td>
<td>3.97E+10</td>
<td>47.9%</td>
<td>7000</td>
<td>2.780E+14</td>
</tr>
<tr>
<td>Agricultural</td>
<td>2.99E+10</td>
<td>36.1%</td>
<td>1380</td>
<td>4.126E+13</td>
</tr>
<tr>
<td>Swamp/Bottomland Forest</td>
<td>7.24E+09</td>
<td>8.7%</td>
<td>12500</td>
<td>9.055E+13</td>
</tr>
<tr>
<td>Water</td>
<td>4.04E+09</td>
<td>4.9%</td>
<td>2000</td>
<td>8.080E+12</td>
</tr>
<tr>
<td>Marsh</td>
<td>1.46E+09</td>
<td>1.8%</td>
<td>12500</td>
<td>1.825E+13</td>
</tr>
<tr>
<td>Rice Paddy</td>
<td>5.02E+08</td>
<td>0.6%</td>
<td>1560</td>
<td>7.831E+11</td>
</tr>
<tr>
<td><strong>Totals:</strong></td>
<td><strong>8.29E+10</strong></td>
<td></td>
<td></td>
<td><strong>4.370E+14</strong></td>
</tr>
</tbody>
</table>

Table 4.5: Estimated South Carolina Land Cover and NPP for Agricultural Age

Energy flows for the peak of the agricultural age are shown in figure 4.2 below.

The energy flows in figure 4.2 were calculated using the following assumptions. It was assumed that of the human food energy 20 percent was egested and 80 percent was assimilated and respired; and of the fodder 50 percent was assimilated and 45 percent was respired (Ricklefs, 1983). All of the firewood was assumed to be burned and therefore respired. The exports consist of rice and animal production.

![Figure 4.2: Digraph of Energy Flows in the Agricultural Biotic/Anthropic System]

The pristine age anthroposphere was ecomimetic because it used only energy from sun driven processes (ANRES=0) and was in a climax state (inputs equal to
outputs). In order to look at the sustainability of the Agricultural Age, Table 4.6 has been assembled with the appropriate metrics.

<table>
<thead>
<tr>
<th>Metric (all metrics in kcal)</th>
<th>Pristine Age</th>
<th>Agricultural Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANRES</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Inputs (HANPP-FNPP+ARES+AI)</td>
<td>7.85E10</td>
<td>2.78E13</td>
</tr>
<tr>
<td>Outputs (AR+AW+AE)</td>
<td>7.85E10</td>
<td>2.78E13</td>
</tr>
<tr>
<td>TNPP</td>
<td>7.04E14</td>
<td>4.37E14</td>
</tr>
<tr>
<td>RNPP</td>
<td>7.04E14</td>
<td>4.09E14</td>
</tr>
<tr>
<td>HANPP</td>
<td>7.85E10</td>
<td>2.948E14</td>
</tr>
<tr>
<td>RNPP/TNPP</td>
<td>99.99%</td>
<td>93.6%</td>
</tr>
<tr>
<td>HANPP/TNPP</td>
<td>0.01%</td>
<td>67.5%</td>
</tr>
<tr>
<td>Ecological Sustainability</td>
<td>Sustainable?</td>
<td>Not Sustainable</td>
</tr>
</tbody>
</table>

Table 4.6: Summary of key metrics Pristine and Agricultural Ages

The trend for the agricultural age is not sustainable because RNPP is decreasing and HANPP is increasing with respect to TNPP.

4.3 South Carolina Energetics: Industrial Age from 1900 to Present

Starting in about 1895, South Carolina underwent a fundamental economic change. The state began its industrial revolution in the form of the textile boom (Edgar, 1998). The hydro powered textile mills signaled the beginning of the end of the prominence of human and animal muscle power and were a precursor to the age of fossil fuels. The agriculture and silviculture sectors remain important in South Carolina’s economy; however, the industrial sector has grown greatly. Table 4.7 below shows crop production as only 0.77 percent of total exports in 2000. The USDA estimated South Carolina’s total agricultural exports at $235.5 million in 2000, which is less than three percent of total exports (2003).
<table>
<thead>
<tr>
<th>Rank</th>
<th>Sector</th>
<th>Value ($x1000)</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chemical Manufactures</td>
<td>1,734,192</td>
<td>20.25%</td>
</tr>
<tr>
<td>2</td>
<td>Transportation Equipment</td>
<td>1,476,846</td>
<td>17.24%</td>
</tr>
<tr>
<td>3</td>
<td>Machinery Manufactures</td>
<td>1,350,587</td>
<td>15.77%</td>
</tr>
<tr>
<td>4</td>
<td>Plastic &amp; Rubber Products</td>
<td>716,816</td>
<td>8.37%</td>
</tr>
<tr>
<td>5</td>
<td>Paper Products</td>
<td>572,189</td>
<td>6.68%</td>
</tr>
<tr>
<td>6</td>
<td>Fabric Mill Products</td>
<td>480,203</td>
<td>5.61%</td>
</tr>
<tr>
<td>7</td>
<td>Computers &amp; Electronic Prod.</td>
<td>415,400</td>
<td>4.85%</td>
</tr>
<tr>
<td>8</td>
<td>Apparel Manufactures</td>
<td>412,628</td>
<td>4.82%</td>
</tr>
<tr>
<td>9</td>
<td>Fabricated Metal Products</td>
<td>268,389</td>
<td>3.13%</td>
</tr>
<tr>
<td>10</td>
<td>Elec. Eq.- Appliances &amp; Parts</td>
<td>238,208</td>
<td>2.78%</td>
</tr>
<tr>
<td>11</td>
<td>Processed Foods</td>
<td>146,758</td>
<td>1.71%</td>
</tr>
<tr>
<td>12</td>
<td>Non-Metallic Mineral Mfgs.</td>
<td>137,251</td>
<td>1.60%</td>
</tr>
<tr>
<td>13</td>
<td>Primary Metal Manufactures</td>
<td>126,300</td>
<td>1.47%</td>
</tr>
<tr>
<td>14</td>
<td>Non-Apparel Textile Products</td>
<td>91,434</td>
<td>1.07%</td>
</tr>
<tr>
<td>15</td>
<td>Misc. Manufactures</td>
<td>85,884</td>
<td>1.00%</td>
</tr>
<tr>
<td>16</td>
<td>Crop Production</td>
<td>66,079</td>
<td>0.77%</td>
</tr>
<tr>
<td>17</td>
<td>Spec. Classification Provisions</td>
<td>59,620</td>
<td>0.70%</td>
</tr>
<tr>
<td>18</td>
<td>Wood Products</td>
<td>52,848</td>
<td>0.62%</td>
</tr>
<tr>
<td>19</td>
<td>Mining</td>
<td>31,885</td>
<td>0.37%</td>
</tr>
<tr>
<td>20</td>
<td>Waste &amp; Scrap</td>
<td>29,614</td>
<td>0.35%</td>
</tr>
<tr>
<td>21</td>
<td>Furniture &amp; Related Products</td>
<td>17,891</td>
<td>0.21%</td>
</tr>
<tr>
<td>22</td>
<td>Goods Returned to Canada</td>
<td>13,868</td>
<td>0.16%</td>
</tr>
<tr>
<td>23</td>
<td>Petroleum &amp; Coal Products</td>
<td>12,069</td>
<td>0.14%</td>
</tr>
<tr>
<td>24</td>
<td>Printing &amp; Related Products</td>
<td>11,232</td>
<td>0.13%</td>
</tr>
<tr>
<td>25</td>
<td>Beverage &amp; Tobacco Products</td>
<td>4,222</td>
<td>0.05%</td>
</tr>
<tr>
<td>26</td>
<td>Fishing- Hunting- &amp; Trapping</td>
<td>3,718</td>
<td>0.04%</td>
</tr>
<tr>
<td>27</td>
<td>Used Merchandise</td>
<td>3,353</td>
<td>0.04%</td>
</tr>
<tr>
<td>28</td>
<td>Forestry &amp; Logging</td>
<td>2,719</td>
<td>0.03%</td>
</tr>
<tr>
<td>29</td>
<td>Leather &amp; Related Products</td>
<td>2,044</td>
<td>0.02%</td>
</tr>
<tr>
<td>30</td>
<td>Animal Production</td>
<td>917</td>
<td>0.01%</td>
</tr>
<tr>
<td>31</td>
<td>Oil &amp; Gas Extraction</td>
<td>154</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

| Totals: | 8,565,126 |

Table 4.7: South Carolina Exports in 2000 (US Commerce, 2003)

4.3.1 Technical Energy Consumption:

This section considers technical energy consumption. Technical energy consumption is not total energy consumption. Technical energy consumption only accounts for energy used for technical process fuel, it does not include human, animal, and product feedstock consumption of energy in the form of biomass (Haberl, 2001 I). The total amount of technical energy consumed is termed total primary energy supply (TPES). Thus total technical energy consumption and TPES can be used interchangeably. Final energy consumption (FEC) is TPES minus any energy exports and electrical generation, transfer, and transformer losses.
With the rise of manufacturing came the need for concentrated energy. The solar energy that drove the agricultural age was too diffuse to use directly and could not be concentrated effectively at the beginning of the industrial age. South Carolina has very little wind energy available (Cassidy and Morrison, 2003) and no fossil or nuclear energy resources (South Carolina Energy Office). The state does have considerable flowing surface water about 11,000 miles of permanently flowing rivers and streams (Beasley et al, 1988). The early mills used this flowing water as their energy source and from 1919 to 1984 the state’s major reservoirs and man-made lakes were created to allow the energy from the flowing water to be transformed into electricity (Dahl, 1999). As the state’s energy needs outstripped the available local supply, energy subsidies in the form of nuclear and fossil fuels were imported.

There is no data available for energy usage in South Carolina prior to 1960. We will assume that only biomass based energy was used in SC prior to 1900. Some coal was used starting in 1848 when the Charleston Gas and Light Company (precursor to SCE&G) began supplying some Charleston street lights with gas made from coal (SCANA, 2003). However, it was not until 1911 that Duke Power began operating their first coal fired generating station (a 6,600 kilowatt plant) in Greenville, SC (Duke Energy, 2003). Using the assumption of only biomass energy use prior to 1900, figure 4.3 depicts technical energy usage from 1900 to 2000 assuming linear growth of energy consumption from 1900 to the first data in 1960.
There is more information available concerning technical energy consumption in the modern anthroposphere than has been available prior to 1960, thus allowing a more detailed and more complete assessment of anthropic energy flows. The reader with a deep interest in technological energy flow issues will find the following sections informative. The reader who is less concerned with the details of technical energy flows can jump ahead to the technical energy summary in section 4.3.7 without fear of missing vital information. The technical energy consumption data is generally broken out into five sectors; utility, residential, commercial, industrial, and transportation. These sector divisions will be maintained for this study, however, the residential and commercial sectors will be considered in conjunction due to similarities. Non-technical energy consumption information is not as detailed and therefore, some assumptions will have to
made concerning per capita consumption rates. Technical energy consumption will be explored first followed by bio-energy or non-technical energy.

4.3.2 Overview of Technical Energy Consumption National and State Level

Technical energy consumption information is available for the national level as well as the state level. Figure 4.4 below depicts energy flow for the entire United States for the year 2000. The flows are represented in Sankey diagram form where the thickness of the flow lines represents the magnitude of the energy flows. The units of the figure below are given as “quads” which are quadrillion (1E15) BTUs.

Figure 4.4: Technical Energy Flow in the United States year 2000 (LLNL, 2003)
Figure 4.5 below is a Sankey diagram showing technical energy flows through the various sectors in South Carolina for the year 1999.

South Carolina depends heavily on nuclear, petroleum, coal, and natural gas all of which must be imported. Only 5.3 percent of the energy including hydro, biomass, geothermal, and solar comes from within the state boundaries. The energy accounting method used to create the two technical energy flow diagrams above varies in a fundamental way from the methods used to create ecological energy flow diagrams. In ecological energy accounting methods, the concept of useful energy would correspond to NPP or secondary productivity given in terms of living biomass production which has an energetic or calorific value and the rejected energy would correspond to respiration. However, in the technical energy flow diagrams above the total useful energy does not
represent a product that contains calorific value except perhaps for the non-fuel use of petroleum in the U.S. energy flow diagram. To reconcile the technical energy flow diagrams with ecological energy flow diagrams, all of the energy flowing into the five sectors would flow out as degraded or respired heat energy.

4.3.3 Residential and Commercial Sectors

For this section, it is assumed that technical energy use across both the residential and commercial sector is uniform such that an average usage value is a meaningful measure and that residential and commercial technical energy use varies directly in proportion to population. Technical energy usage in the residential and commercial sectors are considered in the same section for two reasons, first they both use very similar types and quantities of energy as shown in figures 4.6 and 4.7 below and second because for modeling purposes both sector’s energy usage is assumed to vary directly with population. For reference, the population in South Carolina was approximately 2.4 million in 1960 and 4 million in 2000 (US Census, 2003).
Residential energy use outpaced population growth with energy use increasing by a factor of 2.6 and population increasing by a factor of 1.7. Increased usage occurred for electricity and natural gas. The Energy Information Administration (DOE EIA) defines electrical system energy losses as losses incurred in the generation, transmission, and distribution of electricity plus plant use and unaccounted for electrical system energy losses. Electrical losses amounted to a staggering 63 percent of total electricity and 52 percent of the total energy used in the residential sector during the year 2000.
Commercial energy use also outpaced population growth with energy use increasing by a factor of 5.2. Electrical losses were 63 percent of total electricity and 54 percent of the total energy used in the commercial sector during the year 2000.

Energy Density data for the residential and commercial sector was calculated using the 2000 Census block group data.
Figure 4.8: Residential Energy Use Density year 2000

Most of the state requires less than one thousand kcal per square meter for residential energy and some regions around densely populated areas require between 1000 to 6000 kcal per square meter. However the densely populated urban areas can require up to 40 million kcal per square meter. Residential energy usage is most dense in the urban areas of the state including Greenville, Spartanburg, Rockhill, Columbia, and Charleston. Residential energy consumption is not evenly distributed across the area of the state.

Figure 4.9 below shows the commercial energy consumption density for the year 2000. The pattern of energy use is consistent with the residential consumption because both are modeled on population densities. Commercial energy densities are not as large as residential because overall use in the commercial sector is less that the residential sector.
In order to develop a county level summary of all primary technical energy consumption, the residential and commercial energy use data must be tabulated at county level resolution. Since it is assumed that residential and commercial energy consumption is dependant solely upon populations, representative county population percentages can be used. Figure 4.10 below presents South Carolina’s county level population data for the year 2000.
4.3.4 Industrial Sector

Industrial energy use increasing by a factor of 2.8 from 1960 to 2000. Increased usage occurred for electricity and natural gas. Electrical losses accounted for 63 percent of total electricity but only 32 percent of the total energy used in the industrial sector during the year 2000. Figure 4.11 below details the types and amounts of energy used by the industrial sector from 1960 to 2000.

Figure 4.10: South Carolina County Level Population Data (SCIWAY, 2003)
From 1960 to 2000, small growth occurred in the use of coal and petroleum products with the major growth taking place in use of natural gas, wood (as a fuel), and electricity. Hydro power was the only type of consumed energy that decreased in the industrial sector.

Spatial data for industrial sector technical energy consumption is not readily available. However, enough data is available to develop a rudimentary model of industry specific energy consumption. The DOE EIA conducts a periodic audit of energy use in industries which is named the Manufacturing Energy Consumption Survey (MECS). One available set of data lists industry energy usage based on the number of employees, with industries divided into groups based on the North American Industrial Classification System (NAICS). Table 4.8 below summarizes that data.
Another set of data lists industrial sector energy usage totals broken out by fuel type, region (e.g. Southeast) and NAICS code. Some of this data is withheld at the regional level but totals are generally given at the national level. This data was modified such that the amount of fuel used was given as a percentage of the total energy used by that industry code. Given this estimate and the data in table 4.8 above, energy usage by fuel type for an industry in a given NAICS code can be estimated given the number of employees at the facility. Figure 4.12 below compares an estimation of the energy used
by the industries in South Carolina based on information given in the 2001-2002 South Carolina Industrial Directory with actual consumption data for the industrial sector. For a more detailed explanation of this modeling method and detailed data sets, please refer to Appendix B.

![Industrial Energy Use: Data vs Model](Figure 4.12: Industrial Sector Energy Consumption Model vs. DOE EIA Data)

Coal and total petroleum use agree very well between DOE EIA data and the model. Net electricity is close, but the model predicts about 7 trillion less electricity use than the DOE EIA data on average. Natural gas and wood/ process heat values predicted by the model are twice as large as the DOE EIA data. However, it is possible that on average, industry in the rest of the nation uses more natural gas on site to produce electricity. This could explain the lower net or purchased electricity and the higher natural gas values predicted by the model. South Carolina has an abundance of electrical generating capacity and has been a net exporter of electricity since 1975 when the states nuclear stations began coming online. Assuming that electricity production using a
natural gas turbine is 34 percent efficient, the production of an additional 7 trillion kcal of electricity would require about 21 trillion kcal of natural gas. The energy reallocation allows less electricity to be brought in from the utility and justifies some of the additional natural gas usage bringing the model’s remaining (non-generating) gas usage predictions to within 5 trillion kcal of the five year average of DOE EIA data.

The category of “wood and waste” in the DOE EIA usage data was matched with the category of “other” from the MECS data. According to the MECS information, the “other” category includes net steam (the sum of purchases, generation from renewables, and net transfers), and other energy that respondents indicated was used to produce heat and power or as feedstock/raw material inputs. Process heat imports and exports are not included in the DOE EIA energy consumption estimates. The principle industries that generate net steam or process heat from renewable are the forest products industries including wood and paper products industries and the principle industries using feedstock energy sources for process heat are the chemical and petroleum refining industries. The remaining industries do not create large quantities of process heat through the combustion of a feedstock. Most industries are net importers of process heat (with the exception of textile product mills, primary metal industries, and steel mills), importing process heat from utilities or other net exporters of process heat (MECS, 2003). Most of the process heat generated from renewables is generated by the wood and paper products industries. Summing the “other” category values from all of the wood and paper products industries in the industrial model yields a value of 23.6 trillion kcal. This represents the process heat produced when paper products industries burn waste wood from their feedstock processing to create process heat. The five year average “wood and waste” value from
the DOE EIA data is 21.1 kcal, a very small difference. Figure 4.13 below depicts the
adjusted model which takes into account the hypothetical electricity production on site
from natural gas and the division of wood combusted for process heat and other types of
process heat.

![Industrial Energy Use: Adjusted Model vs. EIA Data](image)

If these assumptions are correct, then there are many companies in South Carolina
that are importing process heat. About 21 trillion kcal of process heat is being imported
per year by industries. Process heat imports are not listed in the DOE EIA data;
therefore, further investigation is needed to determine validity of this assumption.

Regardless of the assumptions used to make the model more aligned with the
DOE EIA data, for calculations of the energy density of the industrial sector, the
unmodified model’s predictions provide a close approximation. Figure 4.14 below shows
the industrial sector energy usage calculated from the model in spatial form based on a
zip code level analysis.
Areas of the most intense industrial sector energy consumption include the Simpsonville-Greenville-Spartanburg area, the Greenwood area, the Rockhill area, the Columbia Metro area, the Savannah River Site, the Sumter-Shaw Air Force Base area, the Florence-Darlington area, and the Charleston Metro area. The industrial energy use densities are not as large as the residential and commercial energy use densities, due to the model’s resolution. The industrial sector was mapped using a zip code level resolution while the residential and commercial sectors were mapped using a block group level resolution. The summary data at the end of this chapter will be presented using a county level resolution for all sectors. In order to combine the data, a county level industrial sector energy consumption percentage was calculated. The percentages are based on the industrial energy use model above and so may contain inaccuracies but, in the absence of actual data, should provide a useful estimate. Figure 4.15 below displays the county level industrial energy consumption percentages including percentage of industrial sector workers.
Figure 4.15: County Level Industrial Sector Energy and Employment

4.3.5 Transportation Sector Energy Consumption

For this section, it is assumed that vehicles registered in South Carolina are the sole users of motor gasoline and diesel fuel sold in the state. Total energy consumed by the transportation sector has tripled since 1960, increasing to 94.9 trillion kcal in the year 2000. Motor gasoline comprised 72 percent of the total and diesel fuel 23 percent. The remaining 5 percent was made up of jet fuel, natural gas, aviation gasoline, and
lubricants. This study will focus on motor gasoline and diesel fuel usage. Figure 4.16 below shows the consumption of fuels in the transportation sector from 1960 to 2000.

![SC Transportation Energy (1960-2000)](image)

Figure 4.16: Energy Consumption in the Transportation Sector in kcal (DOE EIA, 2003)

4.3.5.1 Motor Gasoline Consumption

The distribution of gasoline usage or the energy density was calculated based on a county resolution level. Total vehicle registrations in each county are available from the South Carolina Office of Research and Statistics and commuting times for each county are available from the 2000 census (SCORS, 2003; US Census, 2003). Figure 4.17 below was compiled by dividing the total state motor gasoline consumption among the counties assuming that county fuel consumption is a function of the number of vehicles registered in each county weighted by the county’s average commute time which was normalized by the state’s average commute time.
Figure 4.17: County Level Motor Gasoline Consumption Weighted by Commute Time

The largest consumers are the most urban counties even though commute time weighting was incorporated. The counties show a broad range of consumption with the largest consumer, Greenville County, using almost forty times more fuel than the smallest consumer, Allendale County. Motor gasoline consumption density at a county level resolution is shown in figure 4.18 below.
4.3.5.2 Diesel Fuel Consumption

In order to create a spatial representation of diesel fuel usage, it was assumed that diesel fuel was only used by bulk transport vehicles traveling only on interstate highways. Thus the amount of diesel fuel used in a county is a direct function of the length of interstate highway in that county. Figure 4.19 below shows the county level consumption of diesel fuel in South Carolina for the year 2000 based on the above assumptions.
This is a crude estimate of diesel fuel usage especially since there is no division between on-road and off-road diesel usage; however, in the absence of county level diesel receipts this model will suffice. Based on this model, consumption levels vary greatly from county to county ranging from zero in many counties to nearly two trillion kcal in Spartanburg County. Diesel fuel consumption density at a county level resolution is shown in figure 4.20 below.
4.3.6 Utility Sector

The utility sector is not a primary energy using sector, but exists as a converter that changes the energy stored in fuels into electricity energy that is then distributed to and used by the other sectors. A great deal of energy is lost in the conversion and transmission processes. The data from the residential and commercial sectors above show that only 37 percent of the energy input into the utility sector arrives at the point of consumption. Energy inputs into the utility sector are dominated by nuclear and coal. Figure 4.21 below details the energy inputs into the utility sector during the year of 2000.
Spatial generation data is not readily available for the utility sector. However, information detailing nameplate generation capacities and fuel types of the various power stations and energy generation amounts by the various input fuel types (nuclear, coal, and etc.) is available from the DOE EIA. Assuming that all of power stations using a particular fuel type have the same utilization rate (or equipment up time) and are operating at the same percent of rated capacity, an estimate can be calculated that provides an estimate of utility energy generation by county. Electrical generation density by county is shown in figure 4.22 below.
Utility generation is very concentrated, with eight counties producing most of the state’s electricity.

4.3.7 Summary of Technical Energy Consumption

This section provides a summary of the technical energy consumption for the residential, commercial, industrial, and transportation sectors. The consumption data is given at a county level resolution.

The FEC in the state, which excludes electricity exports; and conversion, transformer, and line losses, was 258.7 trillion kcal in the year 2000. This amounts to an average technical energy consumption density of 3114 kcal per square meter for the entire state. The FEC division among sectors is residential 13.39 percent, commercial 9.07 percent, industrial 40.21 percent, and transportation 37.33 percent.

County level percentage of FEC for the residential, commercial, industrial, and transportation sectors is given in figure 4.23 below.
Figure 4.23: County level percentage of FEC year 2000

The figure 4.24 below shows the combined sector energy consumption density on a county level basis for South Carolina in the year 2000.

Figure 4.24: County Level Energy Consumption Density year 2000
Although the average consumption density for South Carolina is 3,114 kcal per square meter, many counties have a lower energy consumption density. The counties with the highest consumption densities are Greenville, Spartanburg, York, Richland, Lexington, Aiken, and Darlington.

4.3.8 Bio or Non-Technical Energy Flows

The South Carolinian biosystem productivity or NPP given by biome type and area is available in table 4.1. Because the SPOT data is spatial, a detailed map of NPP can be generated. The spatial distribution of NPP is shown below in figure 4.25.

![Figure 4.25: NPP in South Carolina per 1990 SPOT data](image)

Figure 4.25 stands in sharp contrast to the technical energy flows in the prior sections. The density variation is much smaller, providing a much smoother energy landscape.

The current area of land devoted to agriculture is less than half of the area estimated for the agricultural age (see table 4.4). Some of the agricultural land has
become urban area and it is possible that a large portion of the agricultural land which was depleted of soil nutrients has become the shrub/scrub land cover that is distributed broadly throughout the state. Figure 4.26 below shows only urban, shrub/scrub, and current agricultural land.

Figure 4.26: Map of Urban, Agricultural, and Shrub/Scrub Land Cover (SPOT 1990)

Agriculture is carried out on a smaller area, but has become more productive due to subsidies of fertilizer, pesticides, and herbicides. South Carolina applied over 480,000 tons of fertilizer during the 2000-2001 growing season (Graham and Pavlasek, 2002). In 2000, South Carolina planted 6.93 billion square meters and harvested 6.61 billion square meters of crops, fruits, and vegetables and gained about 6.7 trillion kcal of energy from the harvest. Therefore, the average NPP for South Carolina’s agricultural land is more
than twice as large as the unsubsidized agricultural NPP of the past or about 3,000 kcal per square meter assuming NPP is triple the harvested edible energy portion (Odum, 1983).

For the year 2000, the average American was served 1,387,000 kcal of food (a 3,800 kcal per day diet), 401,500 kcal of that food was not eaten (USDA, 2000). Of the 985,500 kcal ingested, 788,400 kcal was assimilated and 197,100 kcal or 20 percent was egested (Ricklefs, 1983). Assuming that the net reproductive growth in South Carolina is zero and ignoring the obesity epidemic, we can assume that all of the assimilated energy was respired. Approximately 83 percent of human caloric intake is plant material and the remainder is animal material (Vitousek et al, 1986). The population of South Carolina in the year 2000 was 4,012,012 (US Census, 2003). Human food consumption for the year 2000 in South Carolina was about 4.62 trillion kcal of plant material and 0.95 trillion kcal animal material. Total South Carolina population food discards and egestion sum to 2.4 trillion kcal for the year. No information on domestic pets was considered, however, pets could represent a significant amount of caloric intake.

Livestock production for the year 2000 is detailed in table 4.9 below assuming that herbivores have an assimilation efficiency of 50 percent and a net production of efficiency of 10 percent for a gross production efficiency of 5 percent (Ricklefs, 1983).

<table>
<thead>
<tr>
<th>Specie</th>
<th>Total Weight (grams)</th>
<th>Total Biomass (kcal)</th>
<th>Food Intake (kcal)</th>
<th>Egestion (kcal)</th>
<th>Respiration (kcal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chickens</td>
<td>4.69E+11</td>
<td>9.38E+11</td>
<td>1.88E+13</td>
<td>9.38E+12</td>
<td>8.44E+12</td>
</tr>
<tr>
<td>Cattle</td>
<td>1.96E+11</td>
<td>3.91E+11</td>
<td>7.82E+12</td>
<td>3.91E+12</td>
<td>3.52E+12</td>
</tr>
<tr>
<td>Turkeys</td>
<td>1.52E+11</td>
<td>3.04E+11</td>
<td>6.07E+12</td>
<td>3.04E+12</td>
<td>2.73E+12</td>
</tr>
<tr>
<td>Hogs&amp;Pigs</td>
<td>4.20E+10</td>
<td>8.41E+10</td>
<td>1.68E+12</td>
<td>8.41E+11</td>
<td>7.57E+11</td>
</tr>
<tr>
<td>Catfish</td>
<td>4.45E+08</td>
<td>8.89E+08</td>
<td>1.78E+10</td>
<td>8.89E+09</td>
<td>8.00E+09</td>
</tr>
<tr>
<td>Totals:</td>
<td>8.59E+11</td>
<td>1.72E+12</td>
<td>3.44E+13</td>
<td>1.72E+13</td>
<td>1.55E+13</td>
</tr>
</tbody>
</table>

Table 4.9: Livestock Production Data for 2000: data from (Graham and Pavlasek, 2002)
Food intake is the NPP required to grow the livestock. For the year 2000, 34.4 trillion kcal of agricultural NPP (fodder) was required to grow the livestock produced in South Carolina. Since only 6.7 trillion kcal of agricultural energy was harvested, 27.7 trillion kcal of fodder would have needed to be imported in addition to the 4.62 trillion kcal of plant material needed to support the human population. Thus a total of 32.3 trillion kcal of plant material would have been imported for 2000. At the current average agricultural productivity level in South Carolina (3,047 kcal per square meter), this would require another 10.6 billion square meters of agricultural land or about the same area as currently exists in the scrub/shrub land cover classification. However, the livestock production of 1.72 trillion kcal is larger than the state consumption of animal products allowing for an export of about 770 billion kcal.

Seafood catch of about 12.4 billion kcal could also be exported. Table 4.10 below details the seafood catch from South Carolina’s Coast assuming a gross productivity of 15 percent for aquatic poikilotherms (Ricklefs, 1983).

<table>
<thead>
<tr>
<th>Specie</th>
<th>Total Weight (grams)</th>
<th>Total Biomass Energy (kcal)</th>
<th>Food Intake (kcal)</th>
<th>Respiration (kcal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish</td>
<td>1.40E+09</td>
<td>2.79E+09</td>
<td>1.86E+10</td>
<td>1.58E+10</td>
</tr>
<tr>
<td>Oysters</td>
<td>2.83E+08</td>
<td>5.67E+08</td>
<td>3.78E+09</td>
<td>3.21E+09</td>
</tr>
<tr>
<td>Clams</td>
<td>1.65E+08</td>
<td>3.30E+08</td>
<td>2.20E+09</td>
<td>1.87E+09</td>
</tr>
<tr>
<td>Shrimp</td>
<td>1.78E+09</td>
<td>3.56E+09</td>
<td>2.37E+10</td>
<td>2.02E+10</td>
</tr>
<tr>
<td>Crabs</td>
<td>2.57E+09</td>
<td>5.14E+09</td>
<td>3.43E+10</td>
<td>2.91E+10</td>
</tr>
<tr>
<td>Totals:</td>
<td>6.20E+09</td>
<td>1.24E+10</td>
<td>8.26E+10</td>
<td>7.02E+10</td>
</tr>
</tbody>
</table>

Table 4.10: Seafood Catch Data for 2000 (Graham and Pavlasek, 2002)

In 1999 South Carolina removed 475 million cubic feet of softwood and 239 million cubic feet of hardwood live tree volume from its forests (Conner and Sheffield, 2000). This is equivalent to a NPP consumption of 18.7 trillion kcal of softwood and 14.1 trillion kcal of hardwood. Subtracting the 20 trillion kcal of wood and wood waste
consumed by the residential, commercial, and industrial sectors, there is a remainder of 12.8 trillion kcal of wood products.

Of the wood products produced in the state, some could have been consumed in state and some could have been exported. Per capita, Americans consumed on average 750 pounds of paper and 18 cubic feet of lumber and structural panels in 1994 (SCFC, 2003). This is equivalent to a direct NPP consumption of 1.33 million kcal of paper and 709 thousand kcal for lumber. For South Carolina’s population in 2000 this is an annual consumption of 5.33 trillion kcal for paper and 2.84 trillion kcal for lumber for a total of 8.17 trillion kcal of wood products. After in state consumption is subtracted, there is an exportable quantity of 4.63 trillion kcal of wood products.

4.3.9 Industrial Age Summary

Figure 4.27 below was created by summing all of the technical and natural energy flows discussed above. HANPP is the sum of timber, agricultural, and seafood harvests. ARES is the sum of hydro, solar, wind, and geothermal energy. ANRES is the sum of nuclear and all fossil energy. AI is the imported agricultural product necessary to support the human and domestic animal population. AE is the sum of remaining animal products, wood products, and electricity after in state consumption. AR consists of the wood products used for energy, animal and human respiration, ARES, and ANRES minus electrical exports. AW is the sum of human food waste and egestion, animal egestion, and all wood products consumed in state.
Table 4.11 below summarizes the key metrics of the three ages of South Carolina.

<table>
<thead>
<tr>
<th>Metric (all metrics in kcal)</th>
<th>Pristine Age</th>
<th>Agricultural Age</th>
<th>Industrial Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANRES</td>
<td>0</td>
<td>0</td>
<td>3.51E14</td>
</tr>
<tr>
<td>Inputs (HANPP-FNPP+ARES+AI)</td>
<td>7.85E10</td>
<td>2.78E13</td>
<td>7.31E13</td>
</tr>
<tr>
<td>Outputs (AR+AW+AE)</td>
<td>7.85E10</td>
<td>2.78E13</td>
<td>4.24E14</td>
</tr>
<tr>
<td>TNPP</td>
<td>7.04E14</td>
<td>4.37E14</td>
<td>5.03E14</td>
</tr>
<tr>
<td>RNPP</td>
<td>7.04E14</td>
<td>4.09E14</td>
<td>4.63E14</td>
</tr>
<tr>
<td>HANPP</td>
<td>7.85E10</td>
<td>2.948E14</td>
<td>2.406E14</td>
</tr>
<tr>
<td>RNPP/TNPP</td>
<td>99.99%</td>
<td>93.6%</td>
<td>92.1%</td>
</tr>
<tr>
<td>HANPP/TNPP</td>
<td>0.01%</td>
<td>67.5%</td>
<td>47.8%</td>
</tr>
<tr>
<td>Ecological Sustainability</td>
<td>Sustainable?</td>
<td>Not Sustainable</td>
<td>Not Sustainable</td>
</tr>
</tbody>
</table>

Table 4.11: Summary of key metrics Pristine, Agricultural, and Industrial Ages

Even though the ratio of HANPP to RNPP improved, the industrial age is not ecologically sustainable due to the continuing trend of RNPP decreasing with respect to TNPP.
The trend of South Carolina’s anthropic system has been a continuous move away from ecological sustainability. Both the pristine and the agricultural age were eco-
mimetic because both were sun driven and in a state of climax, however the industrial system became a metastable system. In order to create a climax anthropic system from an energetics standpoint it is only necessary to eliminate all non-sustainable energy inputs by driving the technical energy subsidy to zero and then balance energy inputs and outputs. The next chapter will attempt to create a sustainable system but will begin by moving the anthropic system back towards a climax state.
CHAPTER FIVE
CREATING A SUSTAINABLE ENERGY SYSTEM

The great paradox is that industrialized nations have succeeded by temporarily uncoupling humankind from nature through exploitation of finite, naturally produced fossil fuels that are rapidly being depleted. Yet civilization still depends on the natural environment, not only for energy and material, but also for vital life-support processes such as air and water cycles. The basic laws of nature have not been repealed; only their complexion and quantitative relations have changed, as the world’s human population and its prodigious consumption of energy have increased our power to alter the environment. Accordingly, our survival depends on knowledge and intelligent action to preserve and enhance environmental quality by means of harmonious rather than disruptive technology.

Eugene P. Odum

5.1 Eliminating Non-renewable Energy Subsidies

In order to create a sustainable energy system, the system must be in a state of climax which means that non-renewable energy subsidies must be replace by renewable sources of energy. Therefore, we need to define what alternative renewable energy subsidies are available and how much energy they can provide. There are two types of renewable energy available in South Carolina; energy from direct conversion of solar energy and energy from indirect conversion of solar energy. Direct conversion of solar
energy includes systems such as photovoltaic (PV) systems for electricity generation and active and passive solar systems for gathering thermal energy. Indirect conversion of solar energy includes biomass, wind, hydro, and ocean energy. Geothermal energy is another potentially renewable non-solar energy source, but it will not be considered in this study because South Carolina does not have any geothermal resources. The details of the different potential renewable energy resources for South Carolina are discussed in detail below.

**Solar PV Systems**

Assuming overall solar system efficiency of 10 percent and an average annual solar irradiation of 1.42 million kcal per square meter, solar PV systems in SC will yield about 142 thousand kcal of electrical energy per square meter per annum (Goswami, 2000). Deploying PV systems could decrease TNPP because solar panels and plants cannot coexist in the same space. However, no additional NPP need be coopted by PV systems if they are placed on existing structures. There are currently 3.87 billion square meters of urban or built up land in SC. If the entire area was covered with solar cells, about 550 trillion kcal of energy could be produced. However, it is not feasible to cover all of the urban area with solar cells.

**Process Heat from solar thermal technologies**

Industrial process heat requirements make up most of the industrial energy requirements in the U.S.; with requirements for process steam of 41 percent and direct process heat of 28 percent (Goswami, 2000). Solar thermal collectors can provide some of this process heat. Assuming annual solar irradiation of 1.42 million kcal per square meter and an average overall solar system efficiency of 61 percent, 866 thousand kcal of
solar energy in the form of heat can be gathered per square meter (Goswami, 2000). These systems should be placed atop existing structures as well to avoid decreasing TNPP. Due to the uncertainty of what fuels industry uses to produce process heat and which uses of process heat could be replaced by active solar systems, generating process heat from solar thermal technologies will not be considered in the models that follow. However, given more specific information on industrial process heat requirements, it is an attractive candidate.

**Wood as a Fuel**

Wood is the original biomass fuel of humans, and is still a viable choice for biomass energy. If all of the wood harvested for energy is taken from mixed oak-pine forests, we can assume a NPP value of 6,500 kcal per square meter (Bolin et al, 1979). All of this NPP is not harvestable as table 5.1 below shows.

<table>
<thead>
<tr>
<th>Tree Component</th>
<th>Young Oak-Pine Forest</th>
<th>Climax Deciduous Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem wood</td>
<td>14.0%</td>
<td>33.3%</td>
</tr>
<tr>
<td>Stem bark</td>
<td>2.5%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Branch wood &amp; bark</td>
<td>23.3%</td>
<td>13.1%</td>
</tr>
<tr>
<td>Leaves</td>
<td>33.1%</td>
<td>29.1%</td>
</tr>
<tr>
<td>Fruits &amp; flowers</td>
<td>2.1%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Roots</td>
<td>25.0%</td>
<td>19.0%</td>
</tr>
</tbody>
</table>

Table 5.1: Allocation of Tree NPP (Whittaker, 1975)

Using the values for a young oak-pine forest and assuming that all of the tree parts excluding the leaves, fruits, flowers, and roots can be harvested, about 40 percent of the NPP can be used as an energy source. Therefore, we can expect a harvestable yield of about 2,600 kcal per square meter on an annual basis. Managing native forests for
energy should improve the RNPP to TNPP ratio due to the fact that 60 percent of the forest’s NPP (the leaves, fruits, flowers, and roots) is available for consumers.

**Energy Crops**

There are several crops that can be grown as an energy crop. One of the popular choices is switchgrass which is a warm season grass with an energy content of about 4,455 kcal per kilogram (Brown, 2003). In order to quantify the life cycle energy requirements of an energy crop, the farming process must be examined for energy costs. Assume that fertilizer application represents the major energy input and assume the following fertilizer production energy requirements; 5584 kcal per pound of nitrogen, 314 kcal per pound of potash (K2O), and 1052 kcal per pound of phosphate (Shapouri, 1995).

Table 5.2 below lists the typical fertilizer requirements for various crops.

<table>
<thead>
<tr>
<th>Crop (Unit of Yield)</th>
<th>Pounds Per unit of Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Alfalfa (ton)</td>
<td>60</td>
</tr>
<tr>
<td>Cool Season Grass (ton)</td>
<td>45</td>
</tr>
<tr>
<td>Warm Season Grass (ton)</td>
<td>35</td>
</tr>
<tr>
<td>Pasture (ton)</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 5.2: Approximate nutrient content of selected forages (Gerrish and Roberts, 1997)

Since switchgrass is a warm season grass, it will require about 217 thousand kcal of energy input in the form of fertilizer for every ton of switchgrass produced or 239 kcal per kilogram. Switchgrass yields for South Carolina are expected to be about 5.32 tons per acre or 1.2 kilograms per square meter (BIN, 2003). This gives a net energy yield of about 5,000 kcal per square meter. This analysis assumes that the entire crop is harvested.
Corn Based Ethanol

Ethanol can be produced by fermenting and distilling biomass containing starch or sugars (Brown, 2003). Corn is a potential feedstock that is currently grown in South Carolina. The average corn yield in SC is 75 bushels per acre (Graham and Pavlasek, 2002). Advanced processes can provide a corn to ethanol conversion rate of 2.66 gallons per bushel (Shapouri et al, 1995). The net energy value of ethanol (subtracting life cycle energy inputs) is 5,318 kcal per gallon (Shapouri et al, 1995). Assume that motor gasoline can be directly replaced by pure ethanol fuel. Corn ethanol can directly replace gasoline, however, there are tuning issues such as compression ratios, timing, and fuel air ratios that will need to be altered to achieve similar performance when converting a gasoline engine to operate on pure ethanol as well as material incompatibilities (FAO, 1994). In the interest of simplicity, we will assume that corn ethanol is a direct replacement for gasoline. Also, assume that all life cycle energy inputs required to create ethanol can be supplied by ethanol produced. Using the assumptions above, the net energy produced is about 1.06 million kcal per acre or 262 kcal per square meter of land devoted to growing corn. This analysis assumes that the entire crop is harvested and used in the production process.

Soy Based Biodiesel

Biodiesel can be produced from various vegetable and animal oils by a process known as transesterification. One popular oil seed crop that is used for biodiesel production and currently grown in South Carolina is soybeans. The average soybean yield in SC is 22 bushels per acre (Graham and Pavlasek, 2002). We will assume that one bushel of soybeans weighs 27.2 kilograms, one kilogram of soybeans produces 0.17
kilograms of oil, one kilogram of oil produces one kilogram of biodiesel, the life cycle energy output to input ratio of soy biodiesel is 3.2 to 1, and the energy content of soy biodiesel is about 9,700 kcal per kilogram (USDA and DOE, 1998). Also, assuming that all life cycle energy inputs required to create biodiesel can be supplied by biodiesel produced, then net energy produced per area of farmland in the form of biodiesel can be calculated using the assumptions above. The net energy produced is about 678 thousand kcal per acre or 168 kcal per square meter of land devoted to growing soybeans. This analysis assumes that the entire crop is harvested.

**Anaerobic Digestion**

Anaerobic digestion is conversion of biomass to biogas (methane) using bacteria. The thermodynamic efficiency of the process is approximately 60 percent (Goswami, 2000). Potential feedstocks are wet biomass including sewage, municipal solid waste (MSW), food processing wastes, agricultural wastes, Napier grass, kelp, bagasse, and water hyacinth (Goswami, 2000). Assuming that some energy crop suitable for digestion can be produced with a yield equivalent to switchgrass, 5,000 kcal per square meter, anaerobic digestion could produce biogas with an energy output of 3,000 kcal per square meter of land devoted to growing an appropriate energy crop. This analysis assumes that the entire crop is harvested. Anaerobic digestion can also be used as a technological decomposer for appropriate organic waste streams.

**Thermal Gasification**

Thermal Gasification is the conversion of biomass into producer gas (hydrogen and methane) using combustion and pyrolysis. The thermodynamic efficiency of the process is approximately 60 percent (Goswami, 2000). Potential feedstocks for the
process must be dry biomass which could include an energy crop such as switchgrass or biomass from wood. Thermal gasification can generate producer gas from wood with a yield of 1,560 kcal per square meter of forest. Thermal gasification can generate producer gas from switchgrass with a yield of 3,000 kcal per square meter.

**Pyrolysis**

Pyrolysis is the conversion of biomass into pyrolysis oils in an anoxic environment. The thermodynamic efficiency is assumed to be about 60 percent. Potential feedstocks for the process must be dry biomass which could include an energy crop such as switchgrass or biomass from wood. Energy yields for pyrolysis oils are the same as thermal gasification. Pyrolysis oils are a more attractive alternative than soy based biodiesel based on land required for energy output. However, the oils are acidic making them corrosive and are oxygenated making them unstable which could make diesel replacement with pyrolysis oils problematic (Goswami, 2000).

**Wind Energy**

SC has very little terrestrial wind energy available (Cassidy and Morrison, 2003). Therefore, wind energy is not considered in this study.

**Hydro Power**

It is assumed that SC has already utilized its available hydro power energy resources.

**Ocean Energy**

South Carolina has potential for both wave and tide energy. However, neither wave nor tide energy has matured technologically (IEA, 1997). Therefore, ocean energy is not considered in this study.
Biomass Fired Steam Turbine

Electricity can be produced by steam turbine using wood as a feedstock. The overall thermodynamic efficiency is about 27.3 percent verses a coal fired plant efficiency of 33.3 percent (Goswami, 2000).

Biomass Fired Gas Turbine

Electricity can be produced by gas turbine using a feedstock of biogas, pyrolysis oils, or producer gas with an overall efficiency of about 47 percent (Goswami, 2000).

Summary of Renewable Energy Alternatives:

In summary, heat and electricity can be produced very efficiently by solar thermal and PV systems. If energy is harvested from biomass, the photosynthesis and respiration losses of the producer plants lower the overall efficiency of the process. High quality liquid fuels will require the most land to produce. Gasoline replacement will require much more land per energy unit that any other energy type assuming that gasoline can only be replaced by fuels created from fermented biomass and that fuel oils can be replaced by pyrolysis oils.

5.2 Status Quo Climax Model

Developing a status quo climax model means that current magnitudes of energy consumption remain constant (per capita energy consumption status quo is maintained), while climax requires that non-renewable energy subsidies be zero. In order to drive ANRES to zero, renewable energy substitutes must be used.

Human Caloric Requirements

Human caloric intake remains set at the current U.S. average of 3,800 kcal per person per day consisting of about 4.62 trillion kcal of plant material and 0.95 trillion
kcal animal material. Discards and egestion sum to 2.4 trillion kcal. Assume an average agricultural NPP of 3,000 kcal per square meter and that only one third of that NPP is edible. To meet the vegetable dietary needs of the residents of South Carolina, about 4.6 billion square meters of agricultural land would be needed. Assuming a gross production efficiency of 5 percent for the animals, about 19 trillion kcal of fodder would be needed to grow the 0.95 trillion kcal of animal products. Assuming that the total amount of agricultural NPP can be consumed by the animals, 6.3 billion square meters of agricultural land would be needed to grow fodder. Thus, the total amount of agricultural land needed is 10.9 billion square meters or 2,730 square meters per person.

During the 2000 growing season fertilizer was applied in the following quantities; 73,075 tons of nitrogen, 32,562 tons of phosphate, and 61,487 tons of potash (Graham and Pavlasek, 2002). Assume the following fertilizer production energy requirements; 5584 kcal per pound of nitrogen, 314 kcal per pound of potash (K2O), and 1052 kcal per pound of phosphate (Shapouri et al, 1995). In 2000, South Carolina gained about 6.7 trillion kcal of energy from the harvest. Fertilizer application represented about 923 billion kcal of energy in 2000, therefore the ratio of fertilizer to crop yield in South Carolina is about 0.14 to 1. Given this ratio, the amount of energy needed to produce the fertilizer necessary to meet the caloric requirements of the humans and animals above would be 4.5 trillion kcal.

There is energy available in the discards and egestion from humans and animals. Human discards and egestion amount to 2.4 trillion kcal and animal egestion is about 9.5 trillion kcal. Using anaerobic digestion to process these wastes, about 7.14 trillion kcal of biogas would be produced. In the interest of simplicity, this production-consumption
system will be considered balanced, with the energy of egestion providing the energy necessary to support agricultural production.

**Replacing Coal**

Of the 109 trillion kcal of coal consumed in SC during the year 2000, the electric utilities used 88 percent and the industrial sector used 12 percent (DOE EIA, 2003). The electric utilities used the coal to create electricity which will be considered later, therefore only the industrial sector coal use will be considered here. We will assume that all of the coal consumed by the industrial sector was used directly as boiler fuel to create process heat. There are two options that could be employed to replace the industrial sector coal; burn wood or use active solar systems. However, only wood fuel will be considered here.

To replace the coal with wood, assume that one energy unit of coal can be replaced by 1.2 energy units of wood fuel (Goswami, 2000). In order to replace current industrial coal consumption of 13.1 trillion kcal with wood consumption, about 6.04 billion square meters of oak-pine forest would be required.

**Replacing Natural Gas and LPG with Biogas**

Of the 40.2 trillion kcal of natural gas consumed in SC during the year 2000, the residential sector used 19 percent, the commercial sector 14 percent, the industrial sector 63 percent, and 2 percent was used by both the transportation sector and the electrical utilities (DOE EIA, 2003). The natural gas consumed by the electric utilities will be ignored here and taken up in the electricity generation section. South Carolina also used 4.6 trillion kcal of LPG in the year 2000 (DOE EIA, 2003). The residential and industrial sectors each used about 46 percent of the total with the commercial sector consuming the
remaining 8 percent. We will assume that both natural gas and LPG can be replaced directly by biogas generated either by digestion or thermal gasification.

In order to replace 44 trillion kcal of natural gas and LPG consumption with biogas, about 14.7 billion square meters of agricultural land or 28.2 billion square meters of oak-pine forest would be required. Assume that agricultural land is used for the replacement.

**Replacing Asphalt and Road Oil with Concrete**

In the year 2000, South Carolina used about 514 thousand cubic meters of asphalt and road oil with a heat value of about 5.4 trillion kcal all of which was allocated to the industrial sector (DOE EIA, 2003). In order to use concrete as a replacement, its embedded or embodied energy must be considered. Also, certain assumptions must be made regarding the replacement including: all of the asphalt and road oil was used for paving; concrete and asphalt paving has an equivalent service life; concrete and asphalt paving is applied at an equal thickness. These assumptions allow for a direct volumetric replacement of asphalt with concrete. A review of current sources of embodied energy data by Joanna Glover provides an average embodied energy value of concrete at about 1.2 million kcal per cubic meter (2001). Therefore, creating an equivalent volume of concrete to replace the asphalt and road oil would require 617 billion kcal of energy.

Assuming that wood can directly provide the energy required to create the concrete and using the oak-pine forest yield of 2,600 kcal per square meter, 237 million square meters of forest land would be required to provide the energy needed to manufacture the necessary amount of concrete.
Replacing Motor and Aviation Gasoline with Corn Ethanol

Of the 70 trillion kcal of motor gasoline consumed in SC during the year 2000, the transportation sector used 99.3 percent and the industrial sector used 0.7 percent (DOE EIA, 2003). In order to replace current motor gasoline consumption with corn based ethanol, about 266 billion square meters of agricultural land would be required. The state would have to be 3.2 times larger than its current size and planted completely in corn fields (including the lakes and near ocean waters) in order to supply the current demand for motor gasoline using corn based ethanol.

South Carolina used 101 billion kcal of aviation gasoline in the year 2000 all allocated to the transportation section (DOE EIA, 2003). Using the same values used for motor gasoline above, an additional 385 million square meters of agricultural land would be required to replace aviation gasoline with corn based ethanol.

Replacing Petroleum Fuel Oils, Lubricants, and Other Petroleum Products

Petroleum products to be replaced include the DOE EIA categories of distillate fuel, residual fuel, jet fuel, kerosene, lubricants, and other petroleum products. The other petroleum products category include 16 various petroleum products that are used in the industrial sector (DOE EIA, 2003). South Carolina consumed a total of 41.6 trillion kcal of the above petroleum products during the year 2000. Figure 5.3 below shows the amounts of these fuels consumed in the various sectors.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Distillate Fuel (kcal)</th>
<th>Jet Fuel (kcal)</th>
<th>Kerosene (kcal)</th>
<th>Lubricants (kcal)</th>
<th>Residual Fuel (kcal)</th>
<th>Other (kcal)</th>
<th>Totals (kcal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>6.80E+11</td>
<td>0</td>
<td>7.56E+11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.44E+12</td>
</tr>
<tr>
<td>Commercial</td>
<td>1.06E+12</td>
<td>0</td>
<td>7.56E+10</td>
<td>0</td>
<td>1.01E+11</td>
<td>0</td>
<td>1.24E+12</td>
</tr>
<tr>
<td>Industrial</td>
<td>3.12E+12</td>
<td>0</td>
<td>1.51E+11</td>
<td>4.28E+11</td>
<td>3.35E+12</td>
<td>4.36E+12</td>
<td>1.14E+13</td>
</tr>
<tr>
<td>Transportation</td>
<td>2.26E+13</td>
<td>2.67E+12</td>
<td>0</td>
<td>4.28E+11</td>
<td>7.31E+11</td>
<td>0</td>
<td>2.64E+13</td>
</tr>
<tr>
<td>Utility</td>
<td>8.06E+11</td>
<td>0</td>
<td>0</td>
<td>2.52E+11</td>
<td>0</td>
<td>1.06E+12</td>
<td>1.06E+12</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>2.83E+13</strong></td>
<td><strong>2.67E+12</strong></td>
<td><strong>9.83E+11</strong></td>
<td><strong>8.56E+11</strong></td>
<td><strong>4.43E+12</strong></td>
<td><strong>4.36E+12</strong></td>
<td><strong>4.16E+13</strong></td>
</tr>
</tbody>
</table>

Table 5.3: Petroleum products to be replaced by biodiesel (DOE EIA, 2003)
In order to replace the above petroleum product consumption with soy based biodiesel, about 248 billion square meters of agricultural land would be required. It is not possible for South Carolina to produce enough soy biodiesel to replace the imported petroleum fuel oils. If the entire state including water bodies was devoted to soybean farming, three times the current area would still be needed to meet fuel oil demands.

Assume that the above petroleum product can be replaced with pyrolysis oils. For replacement using wood as a feedstock, 26.7 billion square meters of forest would be required. If an energy crop is used as a feedstock, 13.9 billion square meters of agricultural land would be required. Assume that agricultural land is used for the replacement.

**Replacing Non-Hydro Electric Power**

In the year 2000, South Carolina consumed 66.2 trillion kcal of electricity (not including losses) and exported 53.1 trillion kcal of electricity. Of the energy consumed in state, the residential sector consumed 33 percent, the commercial sector 24 percent, and the industrial sector 43 percent. Only 1.2 trillion kcal was produced by hydro power.

Replacing the remaining 65 trillion kcal of electrical consumption with solar PV would require 458 million square meters of solar cells. Assume that the cells can be mounted on existing urban/built up land area and will not require clearing of any additional land. There are currently 3.87 billion square meters of urban or built up land in SC. Thus, about 12 percent of the current urban land area would need to be fitted with solar collectors.

**Summary of the Status Quo Climax Model**

Table 5.4 below lists in detail the areas required for ANRES energy replacement.
### Land Area Comparisons Present vs Status Quo Climax Model

<table>
<thead>
<tr>
<th>Land Types</th>
<th>SPOT Data</th>
<th>Status Quo Climax Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Land Areas (m²)</td>
<td>Area Percentages</td>
</tr>
<tr>
<td>Forest</td>
<td>40,834,069,840</td>
<td>51.2%</td>
</tr>
<tr>
<td>Agricultural/Grassland</td>
<td>13,227,792,217</td>
<td>16.6%</td>
</tr>
<tr>
<td>Scrub/Shrub</td>
<td>9,997,936,280</td>
<td>12.5%</td>
</tr>
<tr>
<td>Swamp/Bottomland Forest</td>
<td>7,238,164,225</td>
<td>9.1%</td>
</tr>
<tr>
<td>Water</td>
<td>2,343,357,539</td>
<td>2.9%</td>
</tr>
<tr>
<td>Urban/Built Up</td>
<td>3,867,627,041</td>
<td>4.8%</td>
</tr>
<tr>
<td>Marsh/Estuarine</td>
<td>1,963,483,657</td>
<td>2.5%</td>
</tr>
<tr>
<td>Barren</td>
<td>324,806,625</td>
<td>0.4%</td>
</tr>
<tr>
<td><strong>Totals:</strong></td>
<td><strong>79,797,237,424</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

Table 5.4: Summary of Land Areas Required for Status Quo Model

It is not feasible to substitute ARES for all of the fossil and nuclear energy requirements at current consumption levels. In order for South Carolina to reach a climax state under the parameters of this model, it would need to be about four times larger and mostly covered with agricultural land. Replacing gasoline with corn based ethanol requires the largest area of land. If gasoline was eliminated, 266.4 billion fewer square meters of agricultural land would be required.

Attempting to eliminate the state’s ANRES using the current energy consumption rates is not possible. Coming back to the basic understanding of metabolism, the collective metabolism can be lowered by reducing the number of contributing individuals, reducing the individual metabolism, or a combination of the two. South Carolina’s population is growing; therefore, reducing individual metabolism is the preferred method of reducing the collective anthropic metabolism.

### 5.3 World Class Benchmark Model

In order to create a sustainable, eco-mimetic energy system for South Carolina without reducing current population, it is necessary to reduce individual metabolism.
Humans require a certain level of caloric intake to maintain their internal metabolism, thus an average value of what can be considered a healthy caloric intake can be determined. Deciding what is an appropriate level of external metabolism is more difficult. In order to determine how much external metabolism could be reduced without lowering quality of life, a review of other countries was carried out. It was assumed that gross domestic product (GDP) is a reliable indicator of quality of life. Countries with a GDP of greater than $20,000 per capita were chosen for the benchmarking, table 5.5 below lists those countries including data for South Carolina.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Per Capita Gross Domestic Product, 2001</strong></td>
<td><strong>GDP ($/person)</strong></td>
</tr>
<tr>
<td><strong>(in 1995 US dollars)</strong></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Country</td>
</tr>
<tr>
<td>31</td>
<td>Italy</td>
</tr>
<tr>
<td>32</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>33</td>
<td>Canada</td>
</tr>
<tr>
<td>34</td>
<td>Australia</td>
</tr>
<tr>
<td>35</td>
<td>Hong Kong</td>
</tr>
<tr>
<td>36</td>
<td>South Carolina</td>
</tr>
<tr>
<td>37</td>
<td>Singapore</td>
</tr>
<tr>
<td>38</td>
<td>Ireland</td>
</tr>
<tr>
<td>39</td>
<td>France</td>
</tr>
<tr>
<td>40</td>
<td>Netherlands</td>
</tr>
<tr>
<td>41</td>
<td>Belgium</td>
</tr>
<tr>
<td>42</td>
<td>United States</td>
</tr>
<tr>
<td>43</td>
<td>Sweden</td>
</tr>
<tr>
<td>44</td>
<td>Iceland</td>
</tr>
<tr>
<td>45</td>
<td>Germany</td>
</tr>
<tr>
<td>46</td>
<td>Austria</td>
</tr>
<tr>
<td>47</td>
<td>Finland</td>
</tr>
<tr>
<td>48</td>
<td>Norway</td>
</tr>
<tr>
<td>49</td>
<td>Denmark</td>
</tr>
<tr>
<td>50</td>
<td>Japan</td>
</tr>
<tr>
<td>51</td>
<td>Switzerland</td>
</tr>
<tr>
<td>52</td>
<td>Luxembourg</td>
</tr>
</tbody>
</table>

Table 5.5: Per Capita GDP of Selected Countries, 2001 (DOE EIA, 2003)

In order to rank the countries on effectiveness of energy consumption, the ratio of GDP to total primary energy supply (TPES) was compared. Table 5.6 below lists the
countries sorted by TPES per GDP. TPES per GDP or energy used per wealth created can serve as a measure of effective use of energy.

<table>
<thead>
<tr>
<th>Country</th>
<th>Population (millions)</th>
<th>TPES/ Pop (million kcal/person)</th>
<th>TPES/ GDP (kcal/$)</th>
<th>Elec. Cons./ Pop (million kcal/person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switzerland</td>
<td>7.2</td>
<td>38.7</td>
<td>800</td>
<td>6.9</td>
</tr>
<tr>
<td>Japan</td>
<td>127.2</td>
<td>40.9</td>
<td>900</td>
<td>6.8</td>
</tr>
<tr>
<td>Denmark</td>
<td>5.4</td>
<td>36.9</td>
<td>1000</td>
<td>5.6</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>6.7</td>
<td>24.2</td>
<td>1000</td>
<td>4.8</td>
</tr>
<tr>
<td>Austria</td>
<td>8.1</td>
<td>37.8</td>
<td>1100</td>
<td>6.4</td>
</tr>
<tr>
<td>Germany</td>
<td>82.3</td>
<td>42.6</td>
<td>1300</td>
<td>5.9</td>
</tr>
<tr>
<td>Ireland</td>
<td>3.9</td>
<td>38.9</td>
<td>1300</td>
<td>5.1</td>
</tr>
<tr>
<td>Italy</td>
<td>57.9</td>
<td>29.7</td>
<td>1400</td>
<td>4.6</td>
</tr>
<tr>
<td>France</td>
<td>60.9</td>
<td>43.6</td>
<td>1500</td>
<td>6.4</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>0.4</td>
<td>86.6</td>
<td>1500</td>
<td>13.0</td>
</tr>
<tr>
<td>Netherlands</td>
<td>16.0</td>
<td>48.1</td>
<td>1500</td>
<td>5.7</td>
</tr>
<tr>
<td>Norway</td>
<td>4.5</td>
<td>59.0</td>
<td>1500</td>
<td>22.8</td>
</tr>
<tr>
<td>Sweden</td>
<td>8.9</td>
<td>57.4</td>
<td>1700</td>
<td>13.8</td>
</tr>
<tr>
<td>Belgium</td>
<td>10.3</td>
<td>57.4</td>
<td>1800</td>
<td>7.1</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>58.8</td>
<td>40.0</td>
<td>1800</td>
<td>5.3</td>
</tr>
<tr>
<td>Finland</td>
<td>5.2</td>
<td>65.2</td>
<td>2000</td>
<td>13.5</td>
</tr>
<tr>
<td>Australia</td>
<td>19.5</td>
<td>59.4</td>
<td>2500</td>
<td>8.9</td>
</tr>
<tr>
<td>United States</td>
<td>285.9</td>
<td>79.8</td>
<td>2500</td>
<td>11.1</td>
</tr>
<tr>
<td>Singapore</td>
<td>4.1</td>
<td>70.6</td>
<td>2600</td>
<td>6.6</td>
</tr>
<tr>
<td>Canada</td>
<td>31.1</td>
<td>79.8</td>
<td>3500</td>
<td>14.4</td>
</tr>
<tr>
<td>South Carolina</td>
<td>4.0</td>
<td>92.7</td>
<td>3506</td>
<td>16.5</td>
</tr>
<tr>
<td>Iceland</td>
<td>0.3</td>
<td>118.0</td>
<td>3700</td>
<td>23.2</td>
</tr>
</tbody>
</table>

Table 5.6: Comparison of Key Energy Metrics from Selected Countries, 2001 (IEA, 2003)

Switzerland is the country with the best TPES to GPD ratio and will be used as the benchmark. TPES includes the energy required to produce electricity. In this model solar PV will be used to produce electricity, therefore final energy consumption (FEC) is a better measurement to employ. According to the Swiss Federal Office of Energy, Switzerland’s final energy consumption in 2001 was 28.9 million kcal per capita consisting of 22.3 percent electricity, 0.8 percent other (solar, wind, and etc.), 59 percent oil based petroleum products, 13 percent natural gas, 4.3 percent wood and waste, and 0.7 percent coal (Energy Consumption in Switzerland, 2003). If South Carolinians consumed the same amount of energy per capita as the Swiss, then the FEC of South Carolina in the year 2000 would be 116 trillion kcal. These percentages will be used to
calculate the necessary land areas to support the current population of South Carolina at the level of Swiss energy consumption.

5.3.1 Creating the Benchmark Model

**Human Caloric Requirements**

Human caloric intake is a fixed quantity; however it can be reduced from the current U.S. average of 3,800 kcal per person per day. Based on 2,200 kcal per day diet recommended by the FDA assume 300 kcal from animal products (meat and dairy) and 1,900 kcal from plant products. (US HHS, 2000)

Assume an average agricultural NPP of 3,000 kcal per square meter and that only one third of that NPP is edible. To meet the vegetable dietary needs of the over 4 million residents of SC in the year 2000 (2.78 trillion kcal), about 2.78 billion square meters of agricultural land would be needed. Consumption of animal products is 439 billion kcal requiring that additional agricultural land must be devoted to growing fodder. Assuming a gross production efficiency of 5 percent for the animals, about 8.78 trillion kcal of fodder would be needed to grow the 439 billion kcal of animal products. Assuming that the total amount of agricultural NPP can be consumed by the animals, 2.96 billion square meters of agricultural land would be needed to grow fodder. Thus, the total amount of agricultural land needed is 5.74 billion square meters which is just less than half of the current amount of agricultural land.

**Electrical Requirements through Solar Resources**

Using Switzerland’s electricity consumption of 22.2 percent of the total energy consumption, South Carolina would require about 25.8 trillion kcal of electrical energy. The “other” energy category (including wind and solar) totals to 1.2 trillion kcal which
can be discounted because 1.2 trillion kcal is currently produced by hydro power in South Carolina. The 25.8 trillion kcal of electrical energy could be generated by covering 182 million square meters with solar cells or about 4.7 percent of the current urban area.

Once the electrical energy requirements are subtracted from the total energy requirements, a remainder of 89.4 trillion kcal of energy must be provided consisting of 15.1 trillion kcal of natural gas, 68.5 trillion kcal of oil based petroleum products, 5 trillion kcal of wood/waste, and 0.8 trillion kcal of coal.

**Natural Gas Requirements through Biomass Resources**

About 15.1 trillion kcal of natural gas must be replaced with biogas. Using an energy crop would require 5 billion square meters of agricultural land and using wood would require 9.7 billion square meters of forest. Assume that agricultural land will be used.

**Gasoline Requirements through Corn Ethanol**

Swiss gasoline usage is 44.5 percent of the oil based total petroleum products used or 30.5 trillion kcal (Swiss Energy Agency). In order to replace this amount of gasoline with ethanol, about 116.4 billion square meters of agricultural land would be required.

**Diesel and Oil Requirements through Soy Biodiesel**

Swiss diesel and oil usage is 55.5 percent of the total oil based petroleum products used or 38 trillion kcal (Swiss Energy Agency). In order to replace this amount of oil with pyrolysis oil from an energy crop, 12.7 billion square meters of agricultural land would be required.
Coal and Wood Requirements

Overall, 6.7 trillion kcal of wood/waste and 0.8 trillion kcal of coal are required. Assuming that one kcal of coal can be replaced by 1.2 kcal of wood; a total of 7.7 trillion kcal of wood is required. This requirement can be met with 3 billion square meters of forest.

5.3.2 Summary of World Class Benchmark Model

Table 5.7 below summarizes the land required to provide the energy necessary to support the world class benchmark model.

<table>
<thead>
<tr>
<th>Land Types</th>
<th>Land Areas (m^2)</th>
<th>Area Percentages</th>
<th>Land Areas (m^2)</th>
<th>Area Percentages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>40,834,069,840</td>
<td>51.2%</td>
<td>10,000,000,000</td>
<td>12.5%</td>
</tr>
<tr>
<td>Agricultural/ Grassland</td>
<td>13,227,792,217</td>
<td>16.6%</td>
<td>134,100,000,000</td>
<td>168.1%</td>
</tr>
<tr>
<td>Scrub/Shrub</td>
<td>9,997,936,280</td>
<td>12.5%</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Swamp/Bottomland Forest</td>
<td>7,238,164,225</td>
<td>9.1%</td>
<td>7,238,164,225</td>
<td>9.1%</td>
</tr>
<tr>
<td>Water</td>
<td>2,343,357,539</td>
<td>2.9%</td>
<td>2,343,357,539</td>
<td>2.9%</td>
</tr>
<tr>
<td>Urban/Built Up</td>
<td>3,867,627,041</td>
<td>4.8%</td>
<td>3,867,627,041</td>
<td>4.8%</td>
</tr>
<tr>
<td>Marsh/Estuarine</td>
<td>1,963,483,657</td>
<td>2.5%</td>
<td>1,963,483,657</td>
<td>2.5%</td>
</tr>
<tr>
<td>Barren</td>
<td>324,806,625</td>
<td>0.4%</td>
<td>0</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

Totals: 79,797,237,424 100.0% 79,797,237,424 199.9%

Table 5.7: Summary of Land Areas Required for world class benchmark model

Agricultural land requirements again exceed the land area available with gasoline requirements taking up the largest area due to the low yields of corn based ethanol.

Much more agricultural land would be required if fuel oils were produced from vegetable oils instead of pyrolysis oils. This model is unsustainable because HANPP exceeds TNPP.
5.4 Sustainable, Ecomimetic Model

Since it is not possible to create a sustainable, ecomimetic model using predefined anthropic energy flows, this last model will be defined based on available energy. The population of South Carolina remains set at the year 2000 level. Human physiological needs must be met. The HANPP to TNPP ratio must be less than or equal to the current ratio and the RNPP to TNPP ratio must be greater than or equal to the current ratio. The following sections provide details of the model.

Human Caloric Requirements

Human caloric intake remains fixed at the average value of 2,200 kcal per person per day. Thus, the total amount of agricultural land needed is 5.74 billion square meters.

Remaining Agricultural Land

Human caloric intake requires about one half of the agricultural land. The remaining 7.49 billion square meters of agricultural land can be converted to forestland.

Solar Energy

The area of urban land remains fixed at 3.87 billion square meters. According to a study in Norway, the average area of total urban or built up land devoted to residential structures is 25 percent and the average area devoted to industrial, trade, and services structures is 10 percent (Statistics Norway, 2000). Theoretically then, 35 percent of the urban area could be fitted with solar energy gathering equipment. Assume that one half of this potential area could be fitted with solar PV cells due to solar orientation and other building roof issues. Therefore, about 677 million square meters is available for solar cells. This would provide 96.2 trillion kcal of electricity per year.
Scrub/Shrub and Barren Land

Scrub/Shrub and barren land currently amounts to 10.32 billion square meters. This land is converted to forestland.

Remaining Land

The remaining land areas including current levels of upland forest, lowland forest/wetlands, water, and marsh are left at present areas for habitat.

Sustainable, Ecomimetic Model Summary

This model returns a great deal of land to forests, making the area of upland forest about 70% of the total area of the state. Table 5.8 below summarizes the land use of the model.

<table>
<thead>
<tr>
<th>Land Types</th>
<th>SPOT Data</th>
<th>Sustainable, Ecomimetic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Land Areas (m^2)</td>
<td>Area Percentages</td>
</tr>
<tr>
<td>Evergreen Forest</td>
<td>20,976,690,589</td>
<td>25.3%</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>17,612,514,916</td>
<td>21.3%</td>
</tr>
<tr>
<td>Agricultural/Grassland</td>
<td>13,227,792,217</td>
<td>16.0%</td>
</tr>
<tr>
<td>Scrub/Shrub</td>
<td>9,997,936,280</td>
<td>12.1%</td>
</tr>
<tr>
<td>Swamp/Bottomland Forest</td>
<td>7,238,164,225</td>
<td>8.7%</td>
</tr>
<tr>
<td>Water</td>
<td>5,428,284,822</td>
<td>6.5%</td>
</tr>
<tr>
<td>Urban/Built Up</td>
<td>3,867,627,041</td>
<td>4.7%</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>2,244,864,335</td>
<td>2.7%</td>
</tr>
<tr>
<td>Marsh</td>
<td>1,963,483,657</td>
<td>2.4%</td>
</tr>
<tr>
<td>Barren</td>
<td>324,806,625</td>
<td>0.4%</td>
</tr>
<tr>
<td>Totals:</td>
<td>82,882,164,707</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 5.8: Summary of Land Areas Required for sustainable, ecomimetic model

Solar electric generation provides 96.2 trillion kcal of energy which coupled with current hydro power output provides a total ARES of 97.4 trillion kcal of electricity per year. The increase in forest area raises the TNPP of the state to 561 trillion kcal, which allows some forest based biomass to be used. In order to achieve ecological
sustainability as defined in this work, RNPP must be at least 92.1% of TNPP and HANPP must be no more than 47.8 percent of TNPP. Therefore, RNPP must be 516.7 trillion kcal of the total of 561 trillion kcal. This leaves 44.3 trillion kcal for human harvest. Of that total, human caloric intake consumes 11.56 trillion kcal; therefore 32.74 trillion kcal of forest products can be harvested for other uses. Converting those forest products into usable energy yields 19.6 trillion kcal of biogas or pyrolysis oils. Table 5.9 below gives the key metrics for the sustainable, ecomimetic model.

<table>
<thead>
<tr>
<th>Metric (all metrics in kcal)</th>
<th>Pristine Age</th>
<th>Agricultural Age</th>
<th>Industrial Age</th>
<th>Sustainable, Ecomimetic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANRES</td>
<td>0</td>
<td>0</td>
<td>3.51E14</td>
<td>0</td>
</tr>
<tr>
<td>Inputs (HANPP-FNPP+ARES+AI)</td>
<td>7.85E10</td>
<td>2.78E13</td>
<td>7.31E13</td>
<td>1.417E14</td>
</tr>
<tr>
<td>Outputs (AR+AW+AE)</td>
<td>7.85E10</td>
<td>2.78E13</td>
<td>4.24E14</td>
<td>1.42E14</td>
</tr>
<tr>
<td>TNPP</td>
<td>7.04E14</td>
<td>4.37E14</td>
<td>5.03E14</td>
<td>5.61E14</td>
</tr>
<tr>
<td>RNPP</td>
<td>7.04E14</td>
<td>4.09E14</td>
<td>4.63E14</td>
<td>5.17E14</td>
</tr>
<tr>
<td>HANPP</td>
<td>7.85E10</td>
<td>2.948E14</td>
<td>2.406E14</td>
<td>1.837E14</td>
</tr>
<tr>
<td>RNPP/TNPP</td>
<td>99.99%</td>
<td>93.6%</td>
<td>92.1%</td>
<td>92.1%</td>
</tr>
<tr>
<td>HANPP/TNPP</td>
<td>0.01%</td>
<td>67.5%</td>
<td>47.8%</td>
<td>33.4%</td>
</tr>
<tr>
<td>Ecological Sustainability</td>
<td>Sustainable?</td>
<td>Not Sustainable</td>
<td>Not Sustainable</td>
<td>Sustainable</td>
</tr>
</tbody>
</table>

Table 5.9: Summary of key metrics Pristine, Agricultural, Industrial Ages, and Model

The sustainable, ecomimetic model would provide a total FEC of 117 trillion kcal of technical energy per year including solar, current hydro power generation, and biomass energy. Electrical energy would make up 83 percent of the total and biomass energy in the form of biogas or pyrolysis oils would make up the remainder. This amounts to about 29.2 million kcal of technical energy per person.

The per capita FEC is the same as Switzerland’s for 2001. However, the energy mix is completely different. Just over 22 percent of the Swiss FEC was electricity while this model’s energy mix is 83 percent electricity. It is possible to create a sustainable
ecomimetic model at year 2000 population levels, but only with an extreme reduction in
the consumption of liquid and gaseous fuels that is replaced by the consumption of
electricity.
6.1 Discussion of the Results, Recommendations, and Conclusions

This study was initiated to address two weaknesses of IE, a lack of energy flow assessments in the field and a lack of a universal definition of IE. The energy flow assessment of South Carolina revealed that South Carolina began in the pristine age as a self-sufficient climax system. Per capita energy consumption was primarily devoted to physiological needs with an energy mix consisting entirely of biomass. During the agricultural age, South Carolina remained in a climax state but began moving in an ecologically unsustainable direction. Per capita energy consumption increased with a large portion devoted to external metabolism. However, the exclusive biomass energy mix continued requiring a considerable amount of land to meet energy needs. During the industrial age, the state moved further toward ecological unsustainability. Per capita energy consumption grew even larger driven by an increasing external metabolism. The burden of energy supply was shifted somewhat from the natural systems by the addition of fossil fuels to the energy mix.

The study furnishes evidence that natural systems provide a poor metaphor for redesigning anthropic energy systems given the current energy mix and consumption levels. The resultant status quo model is physically impossible based on land area.
limitations. The world class benchmark model reduced energy consumption but was still impossible due to the large requirements for liquid fuels. However, the study furnishes evidence that natural systems can be used as a template for anthropic energy systems if the energy mix is moved towards direct solar energy conversion or if an efficient replacement for liquid fuels is employed. Moving away from liquid fuels will require a fundamental shift in modern energy infrastructure due to the fact that petroleum oils make up on average about 50 percent of the TPES in most developed countries.

The sustainable, ecomimetic model is able to maintain benchmark energy consumption levels by shifting the energy mix towards electricity generated directly from the sun. If the anthropic system is to become a sustainable, ecomimetic system, it cannot rely on the biotic producers as the major source of energy. The anthropic system must develop its own producers, its own technoheterotrophs. Candidate technoheterotrophs are solar thermal and solar PV technologies. The model explored only the use of solar PV. However, solar thermal technologies should be used in conjunction with solar PV where appropriate and could increase FEC due to their higher overall efficiency.

The following recommendations can be used to optimize the sustainable, ecomimetic model. First, evaluate what portion of energy needs can be supplied as heat and use solar thermal to meet those needs. The remainder of the energy requirements should come from solar PV. Wind generation should be explored where it is practical, for example, near shore applications. Agricultural lands and forestlands should be used primarily to meet food and material requirements. Current land use should be evaluated to determine which areas of land can be returned to wetland and bottomland forest preserves due to their high productivities. Assuming that the state’s current ratio’s of
RNPP and HANPP to TNPP are sustainable, a larger quantity of HANPP can be harvested for human use if some land areas are devoted to the most productive biome types and remain undisturbed. In other words, convert as much land to productive biomes as possible and leave that land as a preserve. Harvesting should be carried out on agricultural lands and managed upland forests. Lastly, creative wetland systems should be explored such as constructed wetlands for run-off and other waste stream treatment. These created wetlands can serve a dual purpose as natural treatment of pollution and as habitat (e.g. NPP generators).

As a reminder, HANPP is a human constructed metric and there is not a consensus what level of HANPP is too much. Leveling off HANPP at the current level and maintaining that level may define ecological sustainability in theory only if that current appropriation level is too large for the supporting ecosystem to sustain over an extended period. This modeling as currently constructed provides no system of feedback. Ecosystem NPP is inserted as a constant which does not reflect the actual health of the system which can become less productive if stressed. This could lead to a downward spiral in ecosystem health if a constant level of HANPP is maintained as the system becomes less productive.

In summary based on the results of the energy flow assessments carried out in this study of South Carolina, employing industrial ecology metaphorically fails to create a sustainable energy system even when considering the most energy efficient consumption patterns. Natural systems can only be used as a template to create sustainable, ecomimetic, anthropic energy systems if the energy mix is modified or an efficient substitute for liquid fuels is employed.
6.2 Challenges with Research

Gathering data from a broad range of areas that are not usually associated with each other and then connecting that data will always present challenges. The following list details the greatest challenges with the research:

- Data detailing biomass energy flows is not well tracked
- Data detailing exports is readily available though usually in dollar figures only making it difficult to determine energy flows
- Data tracking imports is almost non-existent
- Industrial energy use data is difficult to obtain
- Land use data for SC is outdated and contradictory. A detailed and up to date data set of land use in South Carolina is needed

6.3 Future Research

The process of gathering, quantifying, and assembling the information for this study opened up many other questions for the author. A few of the key questions for future research are listed below. Future research should be carried out in at least the following areas:

- A more detailed study is needed of the use of HANPP as a metric of ecological sustainability or an indicator of ecosystem health; including effects on food webs and ecosystem structure
- Investigation into appropriate methods to easily measure and track the NPP of an area is needed so that NPP changes can serve as feedback for future modeling
- A detailed investigation of how the most energy effective countries are able to consume much less energy while still generating high per capita GDP should be carried out
- Also, a detailed investigation of why South Carolina consumes much more energy while generating less per capita GDP that the average state should be carried out
- Investigate methods to create efficient replacements for gaseous and liquid petroleum fuels such as hydrogen
• Methods to move FEC away from liquid fuels and take advantage of solar thermal and PV including the social and economic impacts of those moves should be investigated

• Further study should be conducted into pyrolysis oils to determine whether they are viable candidates for the replacement of petroleum oils
REFERENCES


Frosch, Robert A. “Industrial ecology: A philosophical introduction,” *Proceedings of the National Academy of Sciences*, vol. 89, February, 1992, pp. 800-803


Porter, Dwayne E. E-mail to the author. 1 Dec. 2003.


118


SCORS-- South Carolina Office of Research and Statistics. 9 Aug. 2003 <http://www.ors.state.sc.us/default.htm>


USC GIS. *GIS Data Server.* University of South Carolina. 19 June 2003 <http://www.cla.sc.edu/gis/dataindex.html>


APPENDIX A

GLOSSARY OF ACRONYMS
Glossary of Acronyms

ANRES: anthropic nonrenewable energy subsidy
ARES: anthropic renewable energy subsidy
BE: biological ecology
DOE: the Department of Energy of the United States
EIA: Energy Information Administration an agency within the Department of Energy
FEC: final energy consumption
GPP: gross primary productivity
HANPP: human appropriation of net primary productivity
IE: industrial ecology
IEA: the International Energy Agency
NPP: net primary productivity
PNPP: potential or pristine net primary productivity
RNPP: remaining net primary productivity
SD: sustainable development
TNPP: total net primary productivity
TPES: total primary energy supply
USDA: United States Department of Agriculture
APPENDIX B

DATA AND WORKSHEETS