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Biomass Energy Systems Efficiency:
Analyzed through a Life Cycle Assessment

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Preface

During my Master's classes, I became very interested in the Energy Industry. I studied the dynamics of deregulation and thought about developing my thesis around the study of 'how deregulation impacts the development of renewable energy'. I realized however that deregulated energy markets were still too young and little if any concrete data existed on development patterns since deregulation.

During my research process, I determined that the deregulated energy markets would only be impressed by concrete data that clearly defined the benefits of a given renewable energy source over the pervasive fossil energy fuels. In order to assess the pros and cons of energy systems, I decided to concentrate on analyzing the entire life cycle of a given energy system.

I finally decided to study technologies that would increase the development potential of renewable biomass energy systems. I realize that business decisions are usually made based upon monetary figures, so eventually I would like to add concrete economic costs to the various biomass energy components. However, the following analysis of the material, energy, and emission flows through a biomass energy system directly and indirectly influence the economic picture. For example, issues such as climate change will likely increase the liability of building fossil fuel dependent energy systems.

If energy developers and governments are presented with an overall analysis of current and future efficiency potentials, environmental and economic risks, and immediate and long term costs, I expect that renewable energy sources such as biomass will experience increased growth.

Abstract

The question is whether biomass energy development can meet rising global electricity demand amid international concerns over fossil fuel dependence, global warming, and land use conflicts. A causal loop diagram illustrates the interrelationships between factors that positively and negatively influence the development of biomass as a renewable energy fuel. This thesis presents a life cycle assessment (LCA) of biomass energy systems to analyze some of the limiting factors. Limiting factors such as increased land use, fossil fuel use, and corresponding CO_2 emissions influence further international biomass development efforts. The life cycle assessment evaluated alternative processes that might increase efficiency. The LCA revealed that integrating Salix short-rotation forests, biological fertilizers, and integrated gasification technologies into the biomass energy system would reduce fossil fuel use and CO_2 emissions by 74 percent and land use by roughly 97 percent. Biomass energy systems can become much more efficient and competitive sources of renewable electricity by implementing Salix, biological fertilizer, and gasification technologies.

Keywords: Bio-energy; Bio-power; Biomass energy analysis; Life cycle analysis (LCA); Salix (willow) production; Electric power; Gasification; Ash recycling; Sludge recycling

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I appreciate IVL's generosity in providing comfortable living accommodations and office space for my three-month internship. Håkan Stripple deserves much appreciation for coordinating my internship and patiently introducing me to the LCA modeling program, KCL-ECO. Håkan Stripple provided me expert advice during the entire LCA modeling process.

I also wish to extend a special thanks to my parents for all their love and support. Traveling to Sweden was a big step and I could not have done it without them. My parents have modeled the life values of accountability, tenacity, truth, integrity, trust, understanding, dedication, and excellence. And while in Sweden, I have been grateful for the friendship, hospitality, and support of my uncle, Dr. Walter Übelacker.

1. Introduction

The question of how to supply the growing demand for electricity, without causing irrevocable damage to the environment has been a subject of intense debate over the last two decades. The intensity has increased as the threat of global climate change is confirmed and the international community seeks to avert global warming by limiting greenhouse emissions.

The electricity industry is arguably the most significant contributing factor to greenhouse gas emissions. The social and economic forces influencing energy growth and the environmental constraints of the atmosphere are presently at odds, as humans increase their dependence on fossil fuels. Feasible development solutions such as renewable energy sources have been proposed in the past to decrease fossil fuel use.

In the last decade, deregulation and technological development in the electrical industry have increased the potential development of renewable energy systems[1]. Wind and solar development programs have realized sizable increases in the past few years. However, due to the weather dependent nature of these energy systems, there is a need for a third system, which provides base-load renewable energy. Exciting new development efforts are currently supporting the use of biomass renewable energy.

Interest is growing to use one of the oldest fuels known to man to meet the electricity demands of the world. The fuel in question is wood, along with other plant materials. People have been using biomass as fuel ever since our ancestors learned how to start a fire with leaves and twigs. Biomass is still the most important fuel, especially in developing countries [1]. In industrial countries biomass has been displaced by fossil fuels, coal, oil, and natural gas, and by hydroelectric and nuclear power. However due to new more efficient biomass systems, demand increases especially in developing countries, deregulation, and environmental greenhouse issues, biomass is positioned well to meet these demands as a renewable fuel for advanced forms of electricity generation [2].

Traditional biomass systems have been inefficient but technology developments have reduced energy, emission, and material flows through the system thus improving the efficiency of biomass energy systems. Traditional forests provide residue chips but research efforts in Scandinavia have determined that fast growing willow trees, Salix, produce greater biomass wood-chip yields. Biomass technology has also reduced use of traditional energy intensive commercial fertilizer by improving the use of biological fertilizers, made from natural ash and sewage sludge. The efficiency of direct firing boiler electricity production has also been increased with gasification and gas turbine technologies. The question is whether these three major technology developments actually increase the net efficiency of biomass energy system from a life cycle perspective.

A life cycle assessment was conducted to determine what extent alternative Salix biomass fuel, bio-recycled fertilization, and gasification technology affect the net efficiency of the biomass energy system. Implementing the three alternative subsystems into biomass energy systems results in a dramatic increase in net efficiency by decreasing the total fossil energy input, CO_2 emissions, and land requirements.

The growing electricity demand and increasing greenhouse gas emissions can both be ameliorated sustainably by developing modern biomass energy systems that utilize Salix fuel, biological fertilizers, and integrated gasification turbine technologies

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[1] “A system is a group of interacting, interrelated, or interdependent components that form a complex and unified whole…” [3].

2. Background

2.1. Background: Biomass Development

Many external background forces influence the development of biomass power systems. A rapid increase in electricity demand within a deregulated investment market that faces environmental problems such as global warming has all contributed to an interest in developing smaller renewable energy systems, such as biomass.

2.1.1. Increasing World Electricity Demand

Worldwide electricity consumption in 2020 is projected to substantially increase 76 percent over 1997 levels [4]. The strongest long-term growth in electricity consumption is expected to occur in the developing economies of Asia, followed by Central and South America, where many areas will experience a doubling in electricity consumption [4]. The substantial increase in electricity production around the world will contribute further to global CO_2 , SO_x , and NO_x emissions.

The increasing demand for electricity results from rapid population growth and economic growth, along with greater industrialization and more widespread household electrification. Much of the world still has limited or no access to electricity so there is much development work needed to address these energy needs.

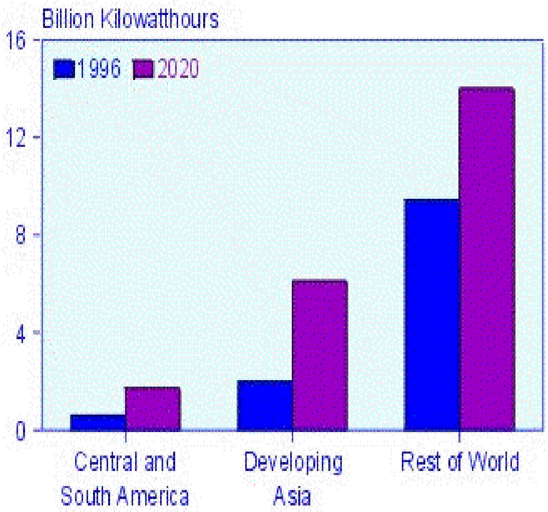

Fig. 1. Global Electricity Demand 1996, 2020 [4]

2.1.2. Micropower and Deregulation

Smaller scale power generation has traditionally been uncompetitive against very large conventional power plants that benefited from economies of scale and vast transmission networks. Increased efficiency of smaller-scale micropower facilities and infrastructure limitations in developing countries and deregulated markets change the dynamics of traditional electricity development in favor of competitive micropower systems.

Thomas Edison, known for his work with electricity, built his first combined heat and power (CHP) facility near Wall Street in New York City in 1882. He envisioned a world of micropower power stations in or near homes and offices providing reliable power and heat in a decentralized independent network [5].

However, development in the power industry over the past 100 years seemed to prove Edison wrong as large macropower stations seemed to grow even larger and move further away from the population centers. In most cases large coal and nuclear stations are located in the countryside depending on extensive grid networks to distribute the electricity. The transmission losses from this centralized distributing network were traditionally outweighed by the economies of scale for the large power facilities [6].

2.1.2.1. Driving Forces of Micropower model

New technologies have emerged in recent years to challenge the traditional electric model. Rapidly developing smaller high efficiency technologies have undermined the former economies of scale argument. Electricity consumers now have the option to generate power locally, utilizing the excess heat in useful applications rather than dumping this energy into rivers, as in the countryside approach.

The reliability of these micro-networks is also increasingly higher than the aging stretched traditional grids that have witnessed severe blackouts in California. These cases are a result of increased demand from the IT sector [7], weak infrastructure maintenance, and minimal increase in supply due to deregulation, which weakened investment in the former capital intensive macropower facilities that experience slow payback periods.

A second driving force behind micropower development is heightened environmental awareness. Stricter environmental and emission standards, prompted by poor local air quality and concern for global warming, have cast doubt on the future acceptance of traditional fossil, hydro, and nuclear facilities.

A third impetus behind micropower development is the deregulation of the energy markets. Deregulation brings common business paradigms into the energy sector. Smaller scale projects are favored because of less initial capital risk and quicker payback periods. Developing countries are also embracing deregulation and privatization as a means of attracting foreign investment and development of electricity facilities to meet their surging demand. Increasing demand, lower reliability, and growing environmental issues are inter-related and create a complex scenario that former government monopolies could not address for economic and political reasons[2][8]. Therefore, deregulation is often viewed as beneficial to both government and the business sectors.

Small local power facilities provide economically competitive generation sources that more accurately satisfy the three main forces discussed above. Like many of the micropower systems that are themselves a century old, such as biomass and gas turbines, Edison's vision might still be realized with the dawn of micropower in the 21st Century.

2.1.2.2. Micropower in developing countries

The greatest potential for micropower may lie in providing reliable access to electricity for over 3 billion individuals in developing countries [5]. Without extensive grid infrastructure, micropower provides an attractive option for providing local needs without spending capital on building a vast grid network. Many of these developing countries have grids that suffer from very poor reliability, resulting in the use of primarily diesel-powered generators [6]. Micropower systems may allow some countries to skip the giant-power-station stage of energy generation completely, just as many countries are currently jumping over wired telephone networks straight into wireless technology. Developing countries can avoid extensive infrastructure by using small-scale local production such as small-scale biomass facilities for India [2]. Corporate energy leaders note that it is already economically feasible to build micropower systems in this context. International agencies such as the World Bank, private-sector operators and non-governmental groups, are financing development efforts to bring electricity to the world's poor [5] with micropower systems such as biomass.

2.1.2.3. Changing the electric grid paradigm

Eventually, micropower may change the way traditional electricity grids in the developed world operate. Shifting from the huge monopolistic generating sources to smaller generation capacity that can be developed by single and small group capital means. Numerous diversified units ranging from solar, wind turbines, fuel cells, and biomass synthesis gas turbines could be linked together to provide a diverse more stable network. These micro-grids provide "greater system reliability, lower operating costs, reduced environmental impact and improved overall business" says ABB's Goran Lindahl [5]. The addition of information technology allows the micro-units and micro-grids to monitor themselves and adjust to energy demands in the market. It is no longer necessary to manually monitor electricity production from new technologies, thus further reducing the need for large facilities built upon economies of scale.

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[2] In Sweden, the contentious issue of closing nuclear facilities was sidestepped by the government handing that responsibility over to deregulated private operators [8].

In the future, even after these regulatory uncertainties are addressed, traditional power stations will not disappear. Capital costs have been committed and the marginal running costs for these facilities are not high. In a deregulated market, market forces such as capital investment and pay back periods will likely favor smaller micropower stations. The notion of micropower will blossom as people realize that the whole concept of producing electricity far from its intended use is as archaic as the idea that every telephone should be attached to a wire [6].

2.1.3. Global Warming

Greenhouse gases such as carbon dioxide prevent heat from leaving the earth, therefore warming the earth's atmosphere. Emissions of CO_2 are expected to swell by 2.1 percent annually, one third of it from the generation of electricity. In addition, 80 percent of the high profile greenhouse gas CO_2 from the USA is produced from power facilities [9], therefore connecting power system development and the issue of global warming.

2.1.3.1. Background on Global Warming

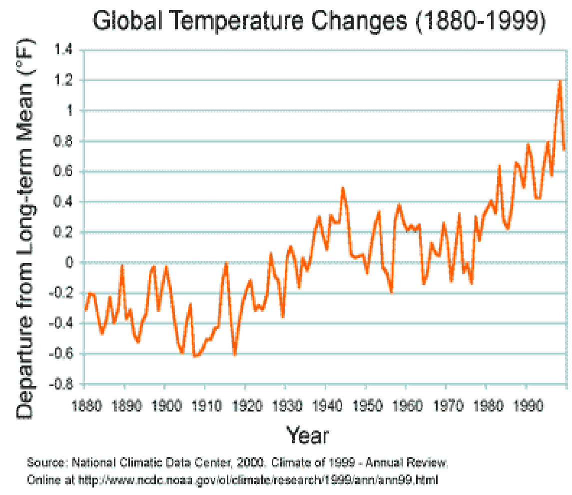
The earth’s climate is changing and is expected to continue changing because human activities are altering the concentration of greenhouse gases (GHG) in the atmosphere. The primary heat-trapping greenhouse gases are CO_2, methane (CH_4), and nitrous oxide (N_2O). GHGs trap heat radiation and inhibit its release back into space, thus, leading to the global climate change [11]. Human activities [11] such as electricity production lead to the increasing GHG levels [12].

“CO_2 and methane (CH_4) are two of the most potent gases that contribute to global warming. Fossil fuels are major contributors to global warming, producing large amounts of CO_2” [10]. Burning biomass emits CO_2 but renewably grown biomass leads to a net zero increase in atmospheric CO_2, because reestablished trees absorb the biogenic CO_2 released during biomass combustion.

2.1.3.2. Greenhouse Gas Emission Increases

In the short period since the beginning of the Industrial Revolution, the atmospheric concentrations of primary greenhouse gases such as CO_2 have increased more than 30 percent, methane concentrations have almost tripled, and nitrous oxide concentrations have risen roughly 15 percent [13]. Emissions of the greenhouse gas carbon dioxide are expected to swell by 2.1 percent annually, one third of it from the generation of electricity [12].

Global mean surface temperatures have increased 0.3 to 0.6 degrees Celsius since the beginning of the industrial revolution, end of the 19th Century. The 10 warmest years in the entire 20th Century occurred in the last 15 years, with 1998 being the warmest year on record [9]. The snow cover in the Northern Hemisphere and floating ice in the Arctic Ocean are both decreasing. Any reduction in the extent of Arctic sea ice and snow cover reduces the albedo, or reflectivity, of the land or ocean surface and allows more solar radiation to be absorbed [14]. Therefore, this effect can be regarded as a positive feedback mechanism for continued warming [14]. Global sea levels have risen 10 to 25 cm over the past century. Global warming has already increased worldwide precipitation over land by 1 percent producing severe flooding around the world [9]. Increasing concentrations of greenhouse gases are expected to accelerate the rate of climate change. Scientists expect that the average global surface temperature could rise up to 6 degrees Celsius by 2100 [9, 16].



Source: National Climatic Data Center, 2000. Climate of 1999 - Annual Review. Online at http://www.ncdc.noaa.gov/ol/climate/research/1999/ann/ann99.html

Fig. 2. Global Temperature Change 1880-1999

2.1.3.3. Causes of global warming: human inducing

What are humans doing to produce these increasing greenhouse concentrations? Burning fossil fuels for energy in most sectors of society such as energy production and transportation and many other human activities are the primary factors responsible for increasing greenhouse emissions. Plant biomass growth and decomposition of organic matter has formed a balanced CO_2 concentration cycle on the earth up until the advent of the Industrial Revolution. Since then, the biomass from millions of years ago in the form of coal and oil has been extracted and burned at increasing rates to fuel our insatiable appetite for energy. These fossil fuels increase net CO_2 concentration[3] in the atmosphere.

Over the last hundred years humans have become more dependent upon fossil fuels for the majority of their energy production. Oil derivatives used to operate automobiles and trucks, heat homes and businesses, power industrial factories, as well as burning coal primarily for electric power production are responsible for roughly 80 percent of society's carbon dioxide emissions, roughly 15 percent of its methane emissions, and roughly 20 percent of global nitrous oxide emissions. Increased rates of artificially based agriculture, deforestation, landfills, industrial production, and mining operations for the extraction of coal also contribute to increasing emissions of greenhouse gases [9].

At the same time that humans are increasing the greenhouse gas emissions, the natural forest systems around the world that absorb and store CO_2 and emit oxygen are being destroyed at phenomenal rates. Today only 1 to 5 percent of the original forest cover of the United States and Europe remains. One third of Asia's forest has been lost since 1960, and half of what remains is severely threatened. Over 13 percent of the natural cover in the Amazon has already been cleared and burned, primarily for cattle pasture [17]. Just in the last decade, vast portions of the forests in Southeast Asia, such as Indonesia, have been cleared. The burning of these valuable forests release so much CO_2 gas and particulate matter into the atmosphere that satellite images can view the burning forests. Not only does this activity release tons of CO_2 but if the trees are not replaced, deforestation also destroys the future CO_2 balancing function of trees, thus accelerating the greenhouse effect.

2.1.3.4. Current International Climate Change Discussions

Key international negotiations on climate change occurred during the 1997 Kyoto conference. The Kyoto Protocol mandated reductions in industrial nations of greenhouse gas emissions by 5 percent below their 1990 levels between 2008 and 2012 [18]. However, the countries did not agree on the mechanisms or actions that would be expected from the member countries to meet the Kyoto commitments.

The 6th Conference of Parties to the 1992 United Nations Framework Convention on Climate Change (COP 6) met November 2000 in The Hague to set a global strategy to reach the Kyoto Protocol targets. For 2 weeks, delegates from 180 countries discussed issues such as emissions trading, forest carbon sinks, binding penalties against non-compliant parties, and financial support for technology transfer. The USA lead coalition of Canada, Australia, and Japan proposed using forest carbon storage, carbon sinks, to offset their fossil fuel emissions. Many groups, including members of the European Union, claimed that the coalition's proposal effectively allowed little if any action to be taken by them on their national levels to reduce the greenhouse gases as agreed upon at the Kyoto convention. Without easier market instruments to achieve the reductions, the USA ultimately refused to make tough decisions to reduce fossil fuel dominated energy consumption.

Countries will ultimately make necessary changes if they have developed the ability to meet the commitments with domestic technology at little additional costs to society. Biomass energy production can provide a means for the USA, Canada, Australia, and other countries to utilize their vast landmass as a sustainable source of renewable biomass energy.

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[3] In 1994, the USA emitted about 1/5 of the total global greenhouse gases [9]

2.1.3.5. Conclusions on Global Warming

Although international conventions have met to discuss ways of stabilizing the growth of greenhouse emissions, projections indicate continued increases in greenhouse gases. It is projected that North America greenhouse emissions will be 42 percent higher than the Kyoto targets by 2010. The International Energy Agency (IEA) stated that “those sobering statistics clearly make the case for more, and more decisive, action to avert unwanted climate change” [19]. The IEA projected that the greatest decrease in greenhouse gases would come from increased use of renewable energy, which could achieve a 3.2 percent reduction, while more cogeneration could drop emissions by an additional 1 percent [19]. Due to the long-term nature of the power industry it is necessary to address development of renewable energy systems now before more capital is sunk into conventional technologies. Biomass energy systems can provide the renewable energy potential that can effectively lower the CO_2 concentration in the atmosphere by reducing the fossil fuel based electricity production and providing a medium to sequester CO_2 in unused biomass crops.

2.2. Background: Biomass Production

In order to decrease the effects of global warming caused by increased greenhouse gases such as CO_2, biomass renewable energy systems are receiving renewed development attention. The subsystems associated with biomass development are also explained.

2.2.1. Biomass Definition

Biomass is defined as organic matter, such as wood, crops, and animal wastes. Solar energy powers photosynthesis, which stores that energy in the form of plant matter. Therefore, biomass is stored solar energy [20].

2.2.2. Advantages of Biomass

Photosynthesis offers a means of harnessing solar energy that deals effectively with two elusive features of sunlight, i.e. the high cost of collection and its intermittence. The collectors involved are simply the leaves of plants, which cost relatively little to grow compared to expensive solar collectors for photovoltaic or solar thermal-electric power options. The plant matter also conveniently provides storage of the biomass energy [10]. Other advantages proposed by Johansson are [10]:

- Biomass is far more widely available than fossil fuels and, with good management practices, can be produced renewably.
- Modernized biomass energy can provide a basis for rural development and employment in developing countries, thereby helping curb urban migration
- In developing countries, growing biomass for energy on deforested and otherwise degraded lands might provide a mechanism for financing the restoration of these lands.
- In industrialized countries, growing biomass for energy on excess croplands can provide a new livelihood for farmers who might otherwise abandon farming because of food crop overproduction.
- If biomass is grown sustainable, its production and use leads to net zero buildup of (CO_2) in the atmosphere, because the CO_2 released in combustion is offset by the CO_2 extracted from the atmosphere during photosynthesis.

To more completely understand the potential roles of biomass as an energy source, it is necessary to study some of the physical and chemical properties.

Because biomass is a solid fuel, comparisons between the properties of biomass and coal are instructive. On a dry-weight basis, heating values[4] range from about 17.5 GJ per ton for various herbaceous biomass feedstock, such as wheat straw, sugarcane bagasse, to about 20 GJ per ton for woody feedstock [21]. The corresponding values for bituminous coal and lignite range from 30 to 35 GJ per ton and 23 to 26 GJ per ton, respectively. At harvest, the moisture levels of biomass range from 8 to 20 percent for wheat straw up to 30 to 60 percent for wood[5] in contrast to the moisture content of most bituminous coals ranging from 2 to 12 percent[6] [10]. Thus, the energy densities for biomass at the point of production are notably less than that of coal.

The low energy density of harvested biomass and the dispersed nature of biomass production have traditionally required that biomass energy facilities be dispersed and relatively small to avoid high transportation costs. The new Salix energy crop provides farmers the opportunity to utilize fast growing higher heating value wood in dense stands. Salix allows the biomass energy system to support larger power facilities on less land.

Although the mass density of biomass has made it less attractive as a fuel than coal, its chemical attributes make it superior in many respects. The ash content of biomass is typically much lower than coal and the biomass ash is generally free of toxic metals and other trace contaminants that make it difficult to dispose of coal ash in environmentally acceptable ways. Furthermore, the ash recovered at biomass power facilities can be dispersed as fertilizer back on the biomass growing area to help recycle the nutrients removed from the site during harvesting. The sulfur (S) content of biomass is also much less than that in coal. Coal contains 0.5 to 5 percent S by weight compared to biomass feedstock S ranging from 0.01 to 0.1 percent. The combustion of coal has lead to major environmental problems, such as acidification, associated with sulfur dioxide (SO_2) emissions [10]. Therefore, biomass energy systems help alleviate acidification.

Biomass is also much more reactive than coal,[7] meaning it is a very attractive feedstock for gasification and the subsequent power generation. The reactivity advantage of biomass can be exploited in the gasification process, leading to higher efficiency and cost-effective modest scale biomass power facilities.

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[4] In this reference, the energy content of fuel is the higher heating value (HHV), which includes the latent heat of condensing the water vapor in combustion product gases. The lower heating value (LHV) does not include the latent heat and is therefore about 6% lower for most biomass feedstocks

[5] Here moisture content, in percent, is measured on a wet basis as: 100 * (mass of contained water)/(mass of the wet biomass). An alternative conversion measures the moisture content on a dry basis.

[6] Sub-bituminous coals often have moisture levels of 15 to 30 percent, the moisture content of lignites can exceed 35 percent.

[7] The greater reactivity of biomass relates to its chemical structure. Neglecting minor chemical constituents, a typical biomass feedstock is chemically represented as $CH_{1.45}O_{0.7}$, compared with $CH_{0.8}O_{0.08}$ for typical coal. Thus, biomass has nearly twice as much hydrogen and nearly an order of magnitude more oxygen per carbon atom than coal.

2.2.3. Electricity from Biomass

2.2.3.1. Introduction

Low efficiency and a dependence on inconsistent sources of biomass residue fuels have limited the development of biomass energy systems. Technological advances in gasification provide a substantial increase of 10 percent efficiency in electrical production. The greater efficiency translates into the ability of the utility to pay for consistent biomass fuels such as Salix.

The technologies already used or potentially useful for biomass power generation are also used or being developed for coal-fired facilities. The primary technical concepts being investigated for biomass power are:
- direct firing of biomass,
- 'co-firing' of biomass with coal;
- gasification of biomass, for firing gas turbines or diesel engines; and
- pyrolysis of biomass, to produce 'bio-crude' liquid fuel to fire diesel engines or gas turbines. [2]

Direct firing refers to simply burning biomass in a boiler to raise steam for a steam turbine-generator. Units of this type are based on the Rankine steam cycle. Due to limited biomass supplies and other background issues that limited the size of biomass systems, the size of these systems were usually only a few megawatts thus further limiting the steam-cycle units already limited efficiency [2]. Small direct-fired biomass power stations have a fuel efficiency of around 25 percent or less. At low efficiency, only low-cost residue fuels can be economically used. These residue fuels however are of limited supply. This was a vicious cycle, where efficiency and supply problems limited development of direct fired biomass facilities.

In recent years, technological advances in gas turbine and gasification technology have raised efficiency of small biomass power facilities up to a respectable 40 percent efficiency [22]. Rather than direct firing, gasification of biomass appears to be the current and future trend of biomass power systems [2]. The 'gasified' biomass produces a combustible gas fuel that can be burned in technologically advanced gas turbines to generate electricity at higher efficiency.

2.2.3.2. Integrated Gas Turbine Gasification Technologies

The gas turbine is typically associated with aviation applications, but it has also evolved into a workhorse for industry. Gas turbines have become the premier electric generation system for peak and intermediate electricity loads. Gas turbines are compact, lightweight, and easy to operate, and come in several sizes ranging from a couple hundred kilowatts to hundreds of megawatts.

A gas turbine combusts a gas fuel to produce high-temperature, high-pressure gas that drives shaft rotation. The resulting gas produces the rotation by exerting pressure on specially designed blades attached to the shaft. The shaft rotation drives an electric generator [23]. The hot exhaust gas can be recycled back to the input airflow to increase efficiency of the turbine and/or it can be used in a combined cycle system to drive a secondary steam turbine for additional electrical production.

Much research by industry and university facilities has yielded greater efficiency and flexibility of gas turbine technology. Turbine manufacturers, General Electric and Siemens-Westinghouse, are conducting major systems development work with some cost-shared cooperation of the US DOE. The utility-scale goal is to achieve greater than 60 percent efficiency in a combined cycle mode with the LHV of natural gas. However, the gas fuel source for gas turbines can also be supplied from gasification of solid fuels [23] such as biomass.

Gasification is the conversion process of choice because it produces a combustible gas that can drive advanced highly efficient gas turbines. Gasification produces combustible synthesis gas (syn-gas) from any hydrocarbon material, such as wood chips, using proven technology.

This reaction or conversion is typically at high temperature and pressure under reducing conditions, with less than half the oxygen required for complete combustion. The biomass feedstock is heated to a temperature of 500 to 600 degrees Celsius driving off some 80 percent of the biomass as volatiles, i.e. as combustible syn-gas. The remaining 20 percent of the carbon (C) in the biomass reacts with a limited supply of oxygen (O) to form carbon monoxide (CO), which is a combustible gas, rather than carbon dioxide (CO_2). Secondly, the water in the biomass reacts to form additional combustible hydrogen gas (H_2) [2]. The gasification process effectively converts the wood chips into a syn-gas composed primarily of carbon monoxide (CO) and hydrogen (H_2) [24]. The syn-gas functions as the fuel powering modern gas turbines to generate electricity, steam, or chemical synthesis.

The raw syn-gas is then purified, usually after cooling, by technologies that are commonly used in natural gas purification and oil refining [25]. The processed gas can then be used in different utility configurations to generate energy.

Integrated Gasification Combined Cycle (IGCC) technology represents an advanced configuration for converting solid feedstock-based energy production into syn-gas and work energy through a gas turbine. The gas turbine drives an electric generator and its exhaust gas is used to produce steam to drive a steam turbine. IGCC is one of the most efficient and environmentally friendly advanced commercial power generation technologies. The improved efficiency of gasification technology allows biomass to be used more competitively as an energy source to meet international electricity demands.

2.2.3.3. International Advanced Biomass Development Projects

The concepts of advanced biomass energy systems have developed beyond theory. The improved efficiency of gasification facilities has lead to full scale development initiatives. Pilot and demonstration facilities incorporating gasification technology and gas turbines have been and are now under development in Scandinavia, the US, Brazil, and the EU [2]. Personal communication has been established with leaders in the following four centers of activity.

Burlington Electric, Vermont, USA:
Biomass has fueled the McNeil Generating Station in Burlington, Vermont since the early 1980s. This facility utilizes biomass chips and residues in a conventional steam boiler to generate up to 50 MW of electricity from its steam turbines. The existing fuel supply and the other infrastructure at McNeil provided a logical site for gasification technology demonstration.

In 1994, the US DOE[8] and the private Future Energy Resources Corporation (FERCO) began funding the development of the wood gasifier at the McNeil facility [26]. Other project partners are Battelle Laboratories, Burlington Electric Department, and the National Renewable Energy Laboratory (NREL).

The gasification project is being conducted in phases. Construction of the gasifier next to the NcNeil facility was completed in 1998 (27). During the second stage, the gasifier operated to produce medium BTU synthesis gas that could be burned in the existing boiler. The project is currently at this second stage, running tests on the operation-integrated system. Ultimately, the gasifier will be integrated with a gas turbine to generate electricity more efficiently. After successfully demonstrating this technology at NcNeil, FERCO plans to refine and market their unique integrated biomass gasification systems throughout North America.

Värnamo Demonstration Plant, Sweden:
Sweden’s forest resources have traditionally been used in direct firing applications, from household furnaces to large district heating systems. Värnamo was the site of the world’s first complete integrated gasification combined-cycle (IGCC) facility to generate electrical and thermal energy from gasified wood fuels [28].

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[8] US DOE is an acronym for the United States Department of Energy

The project was in progress from July 1991 until March 1996 and was financed by the Swedish National Board for Industrial and Technical Development (Nutek), Elforsk AB [9], and Sydkraft AB. [28]. Sydkraft[10] and Ahlstrom[11] joined forces under a joint venture company called Bioflow Ltd[12] to develop the world's first biomass plant (IGCC) facility for power and district heat production [28].

Because this facility was the first in the world, it was designed conservatively, with a modest size and some redundancy of subsystems [2]. These limitations made unit capital costs too high for it to function as a commercially competitive facility. However, the purpose of the facility was to function as a demonstration facility, allowing engineers to perfect the technology and offer commercial biomass systems in the future through Bioflow Ltd.

ARBRE Facility in Yorkshire, UK:
The first commercial gasification facility in Europe is being developed in the UK. The ARBRE facility will generate 10 MW of electricity, providing power for 33,500 people from clean and sustainable wood fuel sources [29].

First Renewables, a Kelda Group company, is collaborating on this renewable energy development with a Swedish company under the name ARBRE Energy. ARBRE stands for ARable Biomass Renewable Energy. The other major partners are TPS[13] of Sweden which supplies gasification technology and other engineering services, the UK Government's Non Fossil Fuel Obligation (NFFO), and the THERMIE Programme of the European Commission [29].

This project is unique in other respects because it is the first gasification facility to incorporate development efforts in wood supply from short rotation coppice (SRC) plantation of Salix [29]. Developers realize that in order to make the facility work, the facility needs a consistent supply of wood chips from local sustainable sources. SRC, consisting primarily of high yielding varieties of Salix and occasionally popular, is being developed to provide wood fuel to the new ARBRE facility.

Bahia[14], Brazil:
The development of biomass based power generation in Brazil seems only natural, considering that it is the leading producer of renewable energy with 90 percent of its electricity hydroelectric and almost a third of its total primary energy supply from biomass. The project involves the installation of a 30 MW biomass IGCC power plant and a eucalyptus plantation in Bahia.

Rapidly rising electricity demand and limited hydroelectric capacity promoted the regional utility to explore the possibility of using biomass. The UN set up GEF[15], administered by the World Bank, to provide development leadership for the project [2]. GEF assists in the development of renewable energy technologies that are judged to be sufficiently close to commercialization. GEF has made substantial investment in biomass integrated gasification combined cycle technology for the Bahia facility and global development [2].

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[9] An energy research and development company that formerly traded as Svensk Energiutveckling AB.

[10] Sydkraft is Sweden's second largest electric utility

[11] Ahlstrom is an international engineering firm based in Finland, one the world's leading suppliers of circulating fluidized-bed (CFB) combustion and gasification of different fuels, including biomass [2].

[12] Bioflow Ltd was formed as a joint venture company to develop and market new gasification technology.

[13] TPS of Sweden refers to the company TPS Termiska Processer AB

[14] Bahia is located in north-eastern Brazil.

[15] GEF was mandated by the UN to promote investment in four key areas of global environmental importance: protection of the ozone layer, support for biological diversity, maintenance of international bodies of water, and control of emissions of CO_2 to the atmosphere.

TPS of Sweden was selected from a competition with Bioflow Ltd to provide Bahia with their low-pressure gasification technology. The final decision for the $100 million Bahia project was expected during the year 2000, but the decision was delayed and TPS anticipates it during 2001.

Conclusion:
Biomass energy systems are experiencing development as these technological advances and the external background issues collectively encourage renewable biomass energy production. Increasing the efficiency of internal biomass subsystems is also necessary to encourage further development.

2.2.4. Alternative Biomass and Fertilization Production

In order to satisfy the demands of a biomass energy system, fast growing alternatives to the traditional forest sources have been developed. Agricultural based energy crops supply much more biomass per hectare with short growing cycles of 3 to 5 years.

2.2.5.1. Alternative Biomass Fuel

The specific type of energy crop chosen for this study was a bush-shaped willow tree of the family *Salix*. There are about 300 species of Salix in northern Europe, Asia, North America, and parts of China. Salix is arguably one of the most efficient sources of biomass grown in temperate climates. Presently, *Salix viminalis* is the most widely used species grown in short-rotation coppice[16] (SRC) willow plantations [30]. However, other species of willow are being tested and already new varieties have been developed.

This plant is grown in agricultural fields using conventional farming practices. The farmer harvests the energy crop every 3 to 5 years for up to 30 years [30]. The biomass production potential for Salix is high, especially in Sweden where research has improved agricultural practices. Christersson reports yields up to 30 oven dry tons (odt) ha^{-1} year^{-1} using present commercial Salix clones with optimized fertilization combined with irrigation [31]. However, average harvested yields of Salix in Sweden[17] are a respectable 9.3 odt ha^{-1} year^{-1}. Börjesson projects average harvest yields of 17 odt ha^{-1} year^{-1} for year 2015 [32].

2.2.5.2. Alternative Fertilizer System

2.2.5.2.1. Bio-Ash Recycling

The growing use of bioenergy places nutrient outflows on the forest and agricultural systems. For example, when logging residues[18] are withdrawn from a forest, up to 70 percent of the above ground nutrient content of the trees are lost [33]. Wood-ash recycling is a means of recycling these nutrient demands back to the forests. Wood ash recycling also effectively reduces the power facility's need for ash deposal, which is an expensive operation.

Before the ash can be returned to the biomass production areas it must be stabilized. The fine particle sizes of the untreated ash cause severe dust problems and the metal oxides may cause damage to human and plant tissues [34]. The untreated wood ash also contains high levels of soluble salts, which could lead to an initial rapid release of alkaline substances and salts, thus disturbing the microorganisms in the soil [35]. In order to avoid such problems, the ash must be mixed with water and CO_2 in the air to stabilize it, technical aspects of the hardening processes are further described in Steenari. The ash will agglomerate, forming larger and denser particles. Finally these larger stabilized ash particles are granulated into a consistency that conventional equipment can spread on forest and biomass crops.

Not all ash is suitable for recycling back to biomass production. Ashes especially from Salix may contain fairly large amounts of cadmium and several heavy metals [36]. However, this obstacle is addressed by burning the biomass at greater than 1000 degrees Celsius, in which case the metals

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[16] Coppice crops re-sprout and re-grow from the root base after being harvested.
[17] Biomass production is assumed to be located in central Sweden, between latitudes 58^0 and 60^0.
[18] Logging/forest residues are the tops and branches.

attach to the fly ash. The fly ash is effectively separated from the bottom ash. Johansson reports that Enköping Värmeverket stores or securely landfills the fly ash and uses the bottom ash in ash recycling operations (appendix 3) [37].

2.2.5.2.2. Sewage Sludge

Salix requires the addition of fertilizers to meet its growth potential. Conventionally manufactured fertilizers nitrogen, phosphorus, potassium, and lime are added in most cases because this is the status quo and other potential sources have not been explored.

Urbanization has lead most people to view wastewater from municipalities as a problem rather than a resource. Policies in Sweden to reach sustainable development have lead to environmental directives for closing nutrient cycles and higher waste deposal fees that promote efforts to re-circulate both organic and inorganic wastes. These policies have encouraged municipalities and biomass energy facilities in Sweden to develop alternative fertilization systems as a means of handling their sewage sludge and ash materials. The nutrient needs of energy agricultural crops can be supplied by the waste products from waste and power systems. Much research especially in Sweden has focused on recycling sludge and other nutrient-rich products back to non-food based agricultural land such as in Enköping, Sweden (appendix 3).

Scientific testing and management of alternative waste and fertilization systems for Salix and other energy crops has taken place in several countries other than Sweden and Denmark, including the UK [38], Poland [39,40]. In these examples the energy crops removed nutrient loads from the wastewater thereby providing two services: treatment of wastewater and fertilization of the energy crops.

SRC Salix plantations are a prime candidate for sewage sludge recycling. Most Salix species show a significant increase in biomass production after sludge application [38]. This study concluded that Salix is a viable energy crop for biofuel as well as providing a route for sludge disposal [38].

The limitations to sludge recycling are concerns about heavy metal content in the sludge. The content of pollutants such as heavy metals and organic compounds has to be low in order to prevent damage to agricultural land [41]. This concern has been addressed by several studies mentioned about that successfully tested these systems without experiencing problems with heavy metals.

Another reason why alternative Salix fertilization systems are so attractive is that Salix actually absorbs many heavy metals. This characteristic can be utilized to treat heavy metal concentrations in contaminated soils associated with mining, industry, and agriculture [42]. Metal accumulation from sludge can also be treated by the natural uptake of metals by Salix. Dickerson, a researcher in the UK, declared “that harvested plants (Salix) could remove at least the same or a larger amount of metal than is being applied to the soil in sludge. Plants (Salix) could then be incinerated and metals in ash then disposed or recovered” [42]. Metal tolerant Salix clones could function as effective means of actually decreasing metal concentrations in soils, providing yet another low-cost environmentally friendly service.

2.2.8.2.3. Sludge and Ash mixture

Research is currently being conducted on the use of a sewage sludge and wood ash mix as fertilizer for Salix energy crops. The sludge and ash is mixed in a 50:50 proportion. Enköping Värmeverket is currently conducting tests of this alternative fertilizer on 120 hectares of Salix fields (appendix 3) [43,37]. As indicated before, the use of sludge and ash separately have been successful and proven feasible. Preliminary assessments concluded that using the sludge and ash materials in combination to supply nutrient and liming requirements of the Salix should be successful.

2.3. Background: Causal Loop Diagram Description

In an effort to clarify the relationship between the main factors influencing this analysis of biomass energy systems, a Causal Loop Diagram (CLD) was constructed. This diagram provides a visual interpretation of the interrelationships between the different actors in the system and the system boundaries.

2.3.1. Definition of a Causal Loop Diagram

Causal Loop Diagrams (CLD) are an effective way to understand the relationships between factors influencing biomass energy system development. The CLD is a method of displaying a system as a "group of interacting, interrelated, or interdependent components that form a complex and unified whole" [3].

Also important for the comprehension of these interactions, the components in these systems have relationships between them, denoted by either a "+" or "-" next to each variable. A "+" indicates that there is a positive relationship between the two components [44]. For example, if the amount of biomass electricity production increases, then the requirement for additional biomass fuel production would also need to increase. Conversely, the "-" next to the variable expresses that there is an opposite relationship between the two. A simple illustration of this association is the increase in the utilization of land use and fossil use causing a decrease in the net efficiency of the biomass energy system.

The interrelationship between factors influencing biomass development is illustrated in Fig. 3.

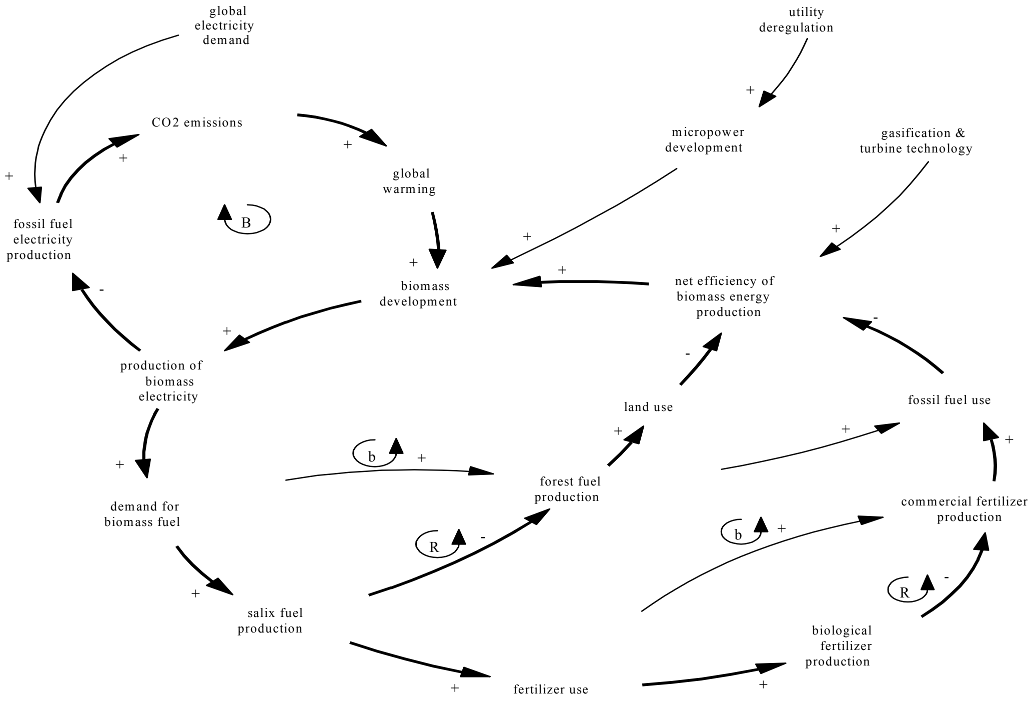

Fig. 3. Broad CLD of influencing factors in biomass energy system development.

2.3.2. Description of Broad CLD

Top-left balancing loop:

At the top left of Fig. 3, the CLD introduces several factors influencing biomass development. The traditional electricity production cycle dependent on fossil fuels increases CO_2 emissions. This increase in greenhouse gas emissions increases global warming. Global electricity demand is exacerbating the problem by reinforcing the demand for electricity production.

In order to solve the reinforcing impact of electricity demand on global warming, the renewable biomass energy system is proposed. The biomass energy system produces net-zero CO_2 electricity that subsequently decreases the fossil fuel electricity production. The decrease in fossil fuel decreases the CO_2 emissions and global warming, effectively balancing the cycle.

Left half of the larger loop:

Decreasing fossil fuel electricity production is dependent on the production of biomass electricity. In order to meet the increasing electricity needs and maintain or reduce fossil fuel electricity production, the biomass system must be reinforcing. Production of biomass electricity requires an increase in the demand for biomass fuels. Forest residue fuels traditionally provided biomass fuels but at the expense of greater land use. The high land use balanced out the production potential of the system.

Salix fuel production is an alternative biomass fuel source that ultimately reduces land use requirements compared to the traditional system. The net result is that the net efficiency of the system is increased and the development and production of biomass electricity can increase in a reinforcing loop to meet the reinforcing tendency of electricity demand on global warming.

Right bottom half of the larger loop:

However, Salix requires fertilizer use. Fertilizer introduces increased energy, material, and emissions into the system. This represents a problem because it decreases the net efficiency of the system by increasing the use of fossil fuel for conventional fertilizer production. Therefore, the biological fertilizer production process was introduced to replace commercial fertilizers and decrease fossil fuel use. The biological fertilizer provides a reinforcing relationship that meets the reinforcing fertilization needs of the Salix production and ultimately increases the net efficiency of the system.

2.3.3. Description of Simplified CLD

The more efficient Salix, biological fertilizer, and gasification technologies effectively increase the efficiency of the biomass system and provide increased biomass electricity production as a reinforcing option to balance the effect of the global warming cycle as shown in Fig. 4.

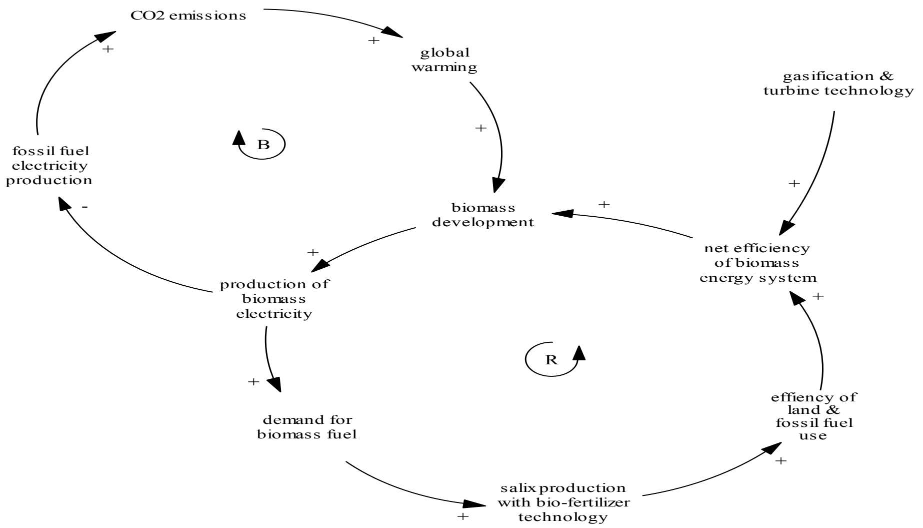

Fig. 4. Simplified CLD of reinforcing biomass loop balancing fossil based electricity.

The energy market demands cost effectiveness, high efficiency, and reduced risk to future emission limits. The following Life Cycle Assessment (LCA) study seeks to determine whether the biomass energy system based on alternative technologies, represented in the lower loop, increases the net efficiency of the system.

3. Methods

3.2. Introduction to the Model

In order to gain an overall efficiency understanding of electrical and heat generation (CHP) from biomass it is necessary to look at the entire life cycle. The production of CHP at a power facility is not the only source of energy use, emissions, and land-requirements. There are numerous other sources of these input and output flows from a life cycle systems perspective.

A holistic view of a biomass was constructed as realistically as possible. The analysis started back at the production of fossil fuels and progresses through processing and transport of the biomass fuels and fertilizers. Finally, the actual conversion of the biomass fuel to heat and electricity was evaluated.

The LCA portion of this study covers the methodology (appendix 1), modeling, and describes different scenario results for the life cycle inventory of biomass energy and power. This study involves performing a life cycle inventory and improvement assessment of the biomass system but not an impact assessment (appendix 1). Therefore, the study is more accurately described as life-cycle inventory (LCI) with an analysis of different scenario results. The computer program, KCL-ECO, is used to calculate the inventory results for the different scenarios [45].

3.2.1. Goal

The objective of this study is to develop a computer model that describes the production and conversion of biomass wood chips into energy from a life cycle perspective. This work can therefore support the growing efforts of research, industry and development organizations in understanding the energy and emissions flows of biomass energy systems by:

- creating a model to better understand the environmental impacts of biomass energy production from a life cycle perspective
- producing valid LCI data that is available for better understanding the system
- obtaining information on ways of optimizing present and future bioenergy systems
- combining the information from different sectors into a more comprehensive picture

3.2.2. Scope: system description and boundaries

In this study the primary material, energy, and emission flows have been traced from the power plant back to fossil fuel and fertilizer production. The model has been designed to accurately quantify the material, energy, and emissions flows.

The reference system shown in Fig. 5 is based on the production reference unit of 1 MWh of electricity. The flows through the biomass production are based on 1 ha of forest or Salix for a period of one year. The specific input and output LCI data is based upon the Enköping CHP facility in Sweden. The operations at this facility direct firing facility are probably more efficient than the global average.

As Fig. 5 illustrates, the primary diesel fuel and fertilizer flows in biomass production are included in this study. Transport services included movement a ton fertilizer, biomass, or waste material flow over one kilometer (ton-km). The seed and seedling, machinery, and facility production are not included in this study. Fig. 5 illustrates the parts of the system covered in this study.

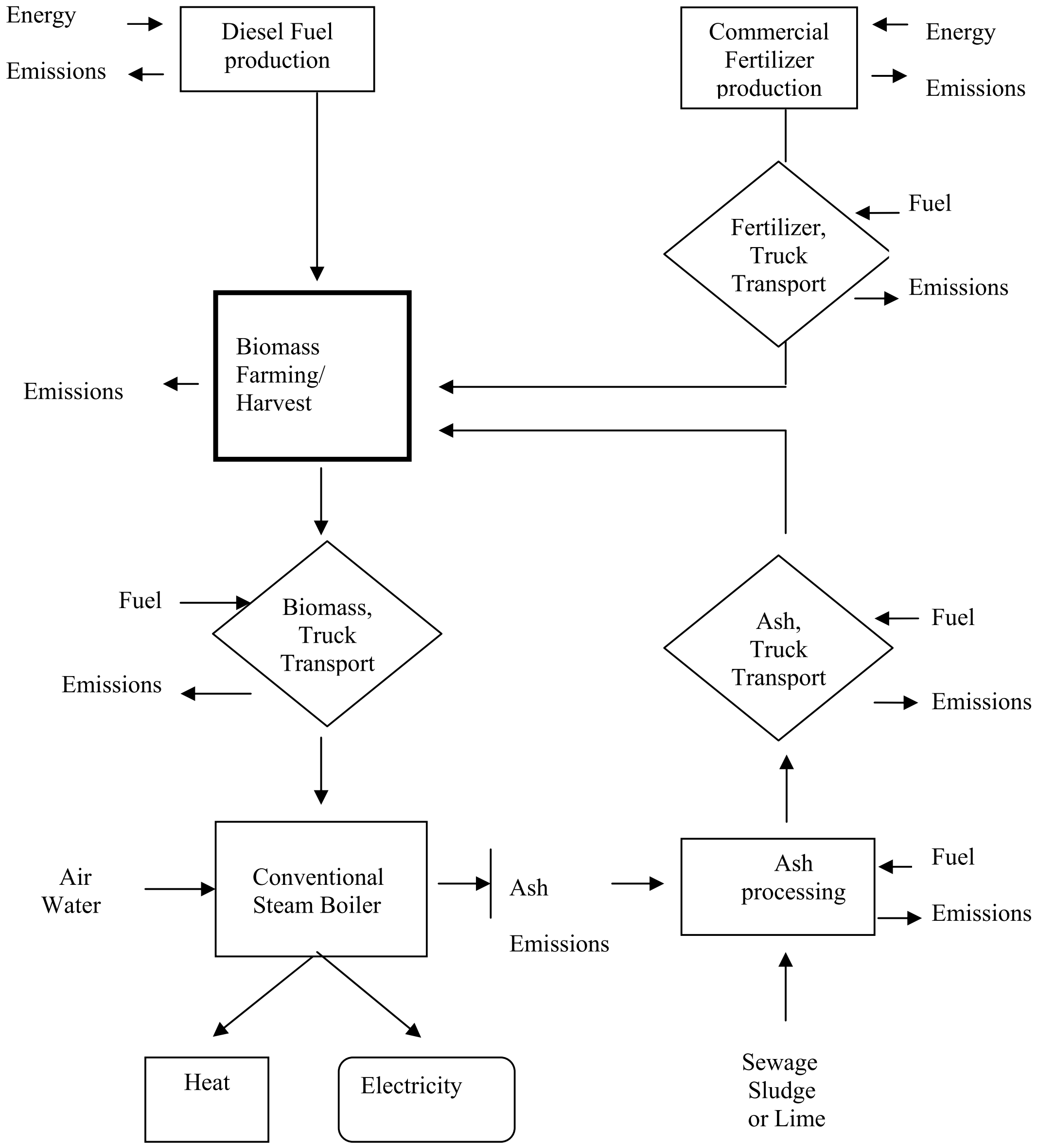

Fig. 5. Flowchart showing the life cycle of biomass production and heat & electricity energy

3.3. Researching LCI information

In order to model the life cycle of biomass heat and electricity production, much research was gathered from many different sources.

3.3.1. Academic data

Former academic research in the form of articles and books proved very useful, especially those from Europe. Much research on biomass energy systems in the United States was grossly outdated and made references to even more archaic data from the 1960s and 1970s [46,47,48]. It became apparent early in the research process that the US had explored the theoretical supplies of biomass energy in the US but not researched a life cycle assessment of the system with concrete values and alternative systems.

Europe, especially Sweden, was soon recognized as the leader in biomass energy research. Research on the traditional use of forest chips and waste materials as well as the alternative Salix energy crop was discovered. The alternative fertilization systems using recycled ash and sewage sludge are also currently being researched and data was available.

3.3.2. Industry data

Data on fuel and emissions for 1999 was requested and analyzed from three biomass facilities in Sweden. CHP facilities in Borås, Nässjö, and Enköping were contacted via email, fax and telephone. A contact individual was established at each site. The contact personnel kindly provided production information for 1999 and answered further questions about the operation of their facilities.

The Enköping was finally chosen as one of the most progressive biomass facilities because they are experimenting with increasing local Salix supplies and utilizing Salix for wastewater and sludge treatment (appendix 3). The subsequent KCL-ECO model was created based upon actual operation data from this facility.

3.4. LCI Data Input into KCL-ECO modeling program

The next step was synthesizing all the acquired data information and integrating it into the model. Each module and flow was described by current data and every effort was made to describe the system in realistic terms.

The data and description of modules and flows are located in Appendix 2 as data sets. The LCI data is presented for the different processes, such as diesel fuel production, production of fertilizers, mixing of alternative fertilizers, wood-chip production, and conversion of wood chips into heat and electricity. These individual processes collectively describe the LCI of the biomass energy model.

The material, energy, and emission flows are calculated and presented for each module per single performance unit, e.g. per MJ diesel oil, Kg fertilizer, logged or farmed hectare. In some modules, equations describe the relationship between variables in the production process.

Transport is not usually calculated in these data sets, but rather calculated separately in the model. Transport between modules is indicated in the model by a ‘hash’ mark through the flow arrow. The data set for trucking transport is also located in Appendix 2.

3.4.1. Introduction to KCL-ECO

In order to help organize all this data and test the biomass production flow, the KCL-ECO life cycle program was utilized [45]. This allows a more user friendly description and testing of the biomass production flow. A model was constructed in this program. The model was composed of square modules that represent given operations. Arrows between the modules represent transfers or ‘flows’ of energy, emissions, or materials.

Fig. 6 illustrates the final model that was creasted in KCL-ECO to represent the life cycle of biomass production.

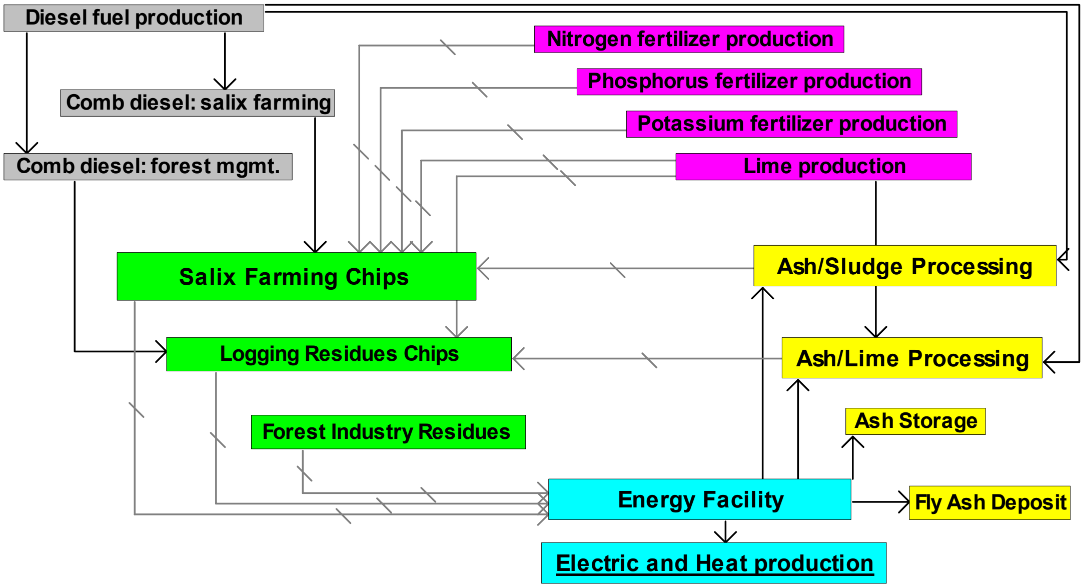

Fig. 6. KCL-ECO flowsheet of the LCI modules

3.4.2. Description of Model

Convention combined heat and electric power (CHP) generation from biomass is produced by burning wood chips in a conventional configuration. The combustion heat produces steam in a boiler driving a steam turbine for electricity production. The exhaust steam is subsequently utilized to provide heat for a district heating system.

The Enköping Värmeverket CHP site was chosen as a reference model because it was the one of the largest facilities and was actively burning a percentage of Salix chips. Peak production at this location is 55 MW of district heating and 22.5 MW net electricity output [49]. Presently the biomass input is limited to 15 percent Salix due to supply limitations and concerns about deposit formation. Both limitations have been resolved in other facilities in Sweden by modifying the boiler to achieve 100 percent Salix chip input [49].

As Fig. 6 illustrates, the corresponding support systems that ensure that the biomass fuel reaches the energy facility are interconnected with the inner model data explained in Appendix 2. The alternative Salix farming and ash/sludge processing systems proposed in this model are explained in the 'Alternative Biomass and Fertilization Production' section. The model allows scenario construction that illustrates the effects of these systems on the overall efficiency of the biomass system.

After completing the modeling work and testing the integrated biomass system, different scenarios representing the overall efficiency and sustainability of the biomass system and its alternative subsystems were designed and analyzed.

4. RESULTS

In the interest of testing the hypothesis and determine the overall sustainability of this biomass system and the proposed alternative subsystems, the model was finally broken down into four scenarios. The first scenario functions as a base case while the remaining three describe the three alternative subsystems.

4.1. Scenario description

Four scenarios were designed to determine to what extent introducing Salix, bio-recycled fertilizer, and gasification technology to biomass energy system impacts the total energy, emission, and land requirements of the system?

Scenario 1:
Scenario 1 provides a base-case view of conventional biomass energy systems. Zero Salix energy crops were incorporated into the fuel stream. Forest-residue chips and industry-wood waste exist in a 90:10 proportion to provide fuel for generating energy. Conventional commercial lime is used to stabilize the pH of the forest soils. Conventional steam-turbine technology provides the only means of electricity production.

Scenario 2:
Scenario 2 provides a view of a Salix chip based biomass energy system, replacing forest-residue chips with Salix chips. Salix chips and industry-wood waste exist in a 90:10 proportion.
Conventional commercial lime, nitrogen, phosphorus, and potassium are used for the Salix farming. Conventional steam-turbine technology provides the only means of electricity production.

Scenario 3:
Scenario 3 provides a view of the alternative bio-recycled fertilizer system, replacing conventional commercial fertilizers for Salix farming. Bio-recycled fertilizer for the Salix farming is the sewage sludge/ash mixture. Salix chips and industry-wood waste exist in a 90:10 proportion. Conventional steam-turbine technology provides the only means of electricity production.

Scenario 4:
Scenario 4 provides a view of the gasification technology option. This technology provides about a 10 percent increase in electricity generation efficiency, reducing the amount of biomass needed to generate 1 MWh electricity. Bio-recycled fertilizer is used for Salix farming. Salix chips and industry wood-waste exist in a 90:10 proportion.

4.2. Results from Scenarios

The LCA results of the four scenarios are presented in Table 1 as specified values per 1 MWh generated biomass electricity. The 'fossil energy input', 'CO_2 emissions', and 'land use' variables were chosen to reveal the overall efficiency of the biomass system. Figures 7, 8, and 9 illustrate the results in graph form.

Fossil energy combustion produces CO_2 emissions, so these two variables follow similar trends but it is still beneficial to separate the energy flow from the corresponding emission flow. The land area needed to generate a given energy value is also crucial because of efficiency and monetary issues.

Table 1. Fossil fuel input (MJ), CO_2 emissions (kg), land use (ha) per 1 MWh produced elec.

Scenarios	Fossil Energy Input (MJ)	CO_2 Emissions (kg)	Land Area Used (hectare)
#1. 0% Salix, std[a]-fertilizers, steam-turbine.	878.9	62.20	2.744
#2. 90% Salix, std[a]-fertilizers, steam-turbine.	691.3	46.22	0.1005
#3. 90% salix, **Bio[b] fertilizers**, Steam-turbine.	313.7	22.50	0.1005
#4. 90% salix, bio[b] fertilizers, **Gas-turbine[c]**.	226.6	16.25	0.07262
% difference b/t scenarios 1 & 4	-74%	-74%	-97%

[b] Standard, 'std', fertilizers refer to conventionally manufactured nitrogen, phosphorus, potassium, and lime.

[c] Biological, 'bio', fertilizers refer to the alternative ash and sewage sludge systems that recycle nutrients.

[c'] Gas-turbine' refers to the introduction of gasification technology combined with efficient gas turbines (IGCC).

5. Discussion

Most current biomass facilities utilize forest residues and waste biomass in a conventional steam turbine. This conventional setup works well but faces several inherent problems that are all interrelated. The primary problem facing systems such as scenario 1 is establishing a stable biomass fuel supply on a limited budget. The limited budget is due in part to the low electrical efficiency in the low to mid 20th percentile for steam turbines. The efficiency of the steam turbine could be improved in larger facilities but then the supply issue must be considered. Supplies of biomass are traditionally from forests, which are limited by low annual production capacity, sparse distribution and increased transport distance. The nature of forest based biomass systems limits the supply of local biomass and thus limits the size of the facility. These factors are all interrelated, providing one local biomass supplies with Salix provides a stable biomass fuel supply

Scenario 1 provides a look at a typical biomass energy facility that operates on forest residues. This scenario quite accurately describes many conventional CHP biomass facilities in Sweden and around the world. Sweden utilizes biomass to meet around 19 percent of its energy needs [50]. Biomass has been so successful in Sweden because the limiting factors are minimized by a large forest industry and small concentrated towns that can efficiently use the excess heat. However in Sweden, more efficient alternatives for utilizing biomass fuel are being explored to further increase efficiency.

Scenarios 2, 3, 4 each illustrates a major step in designing a more efficient biomass energy system. Fossil fuel input, CO_2 emissions, and land use variables represent limiting factors that must be decreased to improve efficiency and the degree of sustainability.

5.1. Fossil Fuel Input (MJ)

The fossil energy input into the biomass system was a critical variable to consider due to objections posted against any system with increasing dependence upon fossil fuel. As Fig. 7 illustrates, the three alternative scenarios 2, 3, 4 proposed in this study lead to decreased fossil fuel energy input per 1 MWh of electricity output.

Diesel fuel use is the primary factor contributing to fossil fuel use in scenario 1, so the first step is to address diesel fuel use in the system. The transition from forest residues to Salix chips in scenario 2 effectively decreases the diesel fuel use in the biomass system by roughly 70 percent. The problem that arises in scenario 2 is the addition of fossil fuel demand from commercial fertilizer, e.g. nitrogen fertilizer, production. With the addition of nitrogen fertilizer production demands, scenario 2 only results in an overall 26 percent decrease in fossil fuel use.

In scenario 3, the change from conventional fertilizers to a more sustainable recycled ash and sludge fertilizer (bio-fertilizer) effectively eliminates the nitrogen fertilizer fossil fuel demand. The substitution of bio-fertilizer for the energy intensive production of nitrogen and other conventional fertilizers results in a significant 51 percent decrease in fossil fuel use. Scenario 3 illustrates clearly that utilizing sewage sludge mixed with nutrient rich wood ash is an extremely effective way to decrease fossil fuel input in the overall biomass energy system.

The final addition of more efficient integrated gasification and gas turbine technologies effectively decreases by 28 percent the biomass fuel demand per 1 MWh electricity produced. The alternative processes, Salix, bio-fertilizer, and gasification, associated with Scenarios 2, 3, and 4 successfully reduced overall system fossil fuel input by a significant 74 percent.

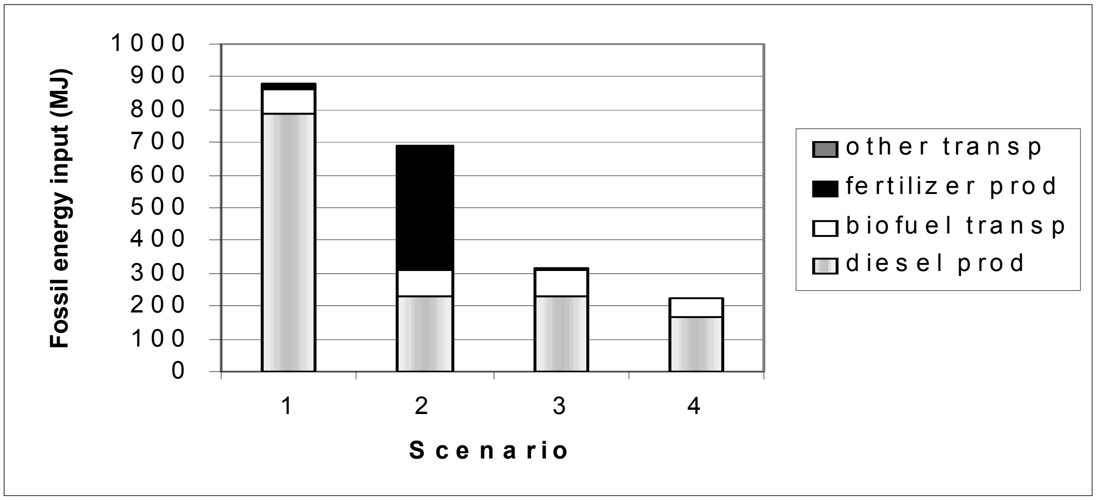

Fig. 7. Fossil energy input (MJ) per 1 MWh generated electricity

5.2. Carbon Dioxide Emissions

CO_2 emissions is an important variable to analyze in light of international concern over greenhouse gas emissions. Parties from all sectors of society are increasingly becoming aware of the relationship between CO_2 emissions and global warming. Therefore, future development of energy facilities should minimize risk by demonstrating concern for this growing problem.

Biomass energy systems are basically CO_2 neutral from the perspective that the CO_2 emissions from biomass fuel are reabsorbed by the growth of sustainable biomass plantations. Fossil fuel use in the production of biomass contributes to the fossil CO_2 emissions. This is why a LCA of the system is critical in evaluating the overall ‘flows’ through the system.

Combustion of diesel fuel is the primary factor contributing to CO_2 emissions in scenario 1, so the first step is to address diesel fuel use in the system, as described in section 5.1. The transition from forest residues to Salix chips in scenario 2 effectively decreases CO_2 emissions in the biomass system by roughly 70 percent. The problem that arises in scenario 2 is the addition of fossil fuel demand from commercial fertilizer, e.g. nitrogen fertilizer, production. With the addition of nitrogen fertilizer production demands, scenario 2 only results in an overall 26 percent decrease in CO_2 emissions.

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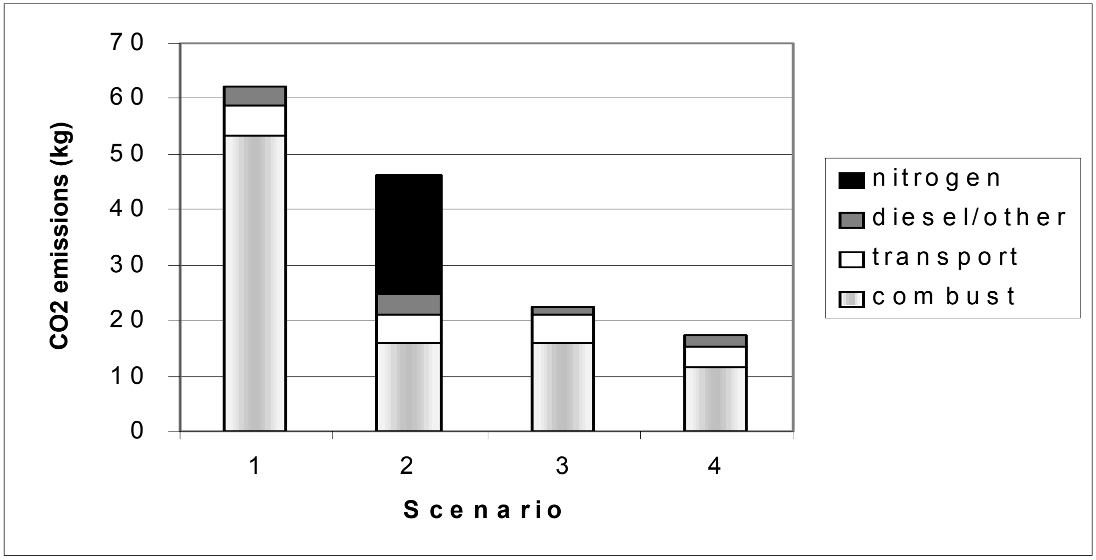

Fig. 8. CO_2 emissions (kg) per 1 MWh generated electricity

5.3. Land Area Required

The land requirement for biomass production is also a critical variable when analyzing the development of biomass energy systems. The burgeoning global population demands increasing food supplies from finite land area. Therefore, biomass systems that produce greater biomass yields on less land while decreasing the energy input can produce biomass for energy production.

In Fig. 9, scenario 1 illustrates that forest residue based biomass systems use several times more land area per energy output than the Salix energy source. Salix supplies an equivalent biomass energy output of 1 MWh electricity at a fraction of the land requirement of forest based systems. As scenario 2 demonstrates, a dramatic reduction in land requirement is achieved by switching from a forest-based source to a Salix energy crop source.

One might question whether the decreased land use is accompanied by increased fossil energy input or emissions flows. But as Fig. 7 and Fig. 8 illustrate, fossil fuel use and CO_2 emission variables also decrease. Therefore, land requirements can be reduced by approximately 97 percent while further increasing the efficiency of the biomass system through implementation of Salix, bio-fertilizer, and gasification operations.

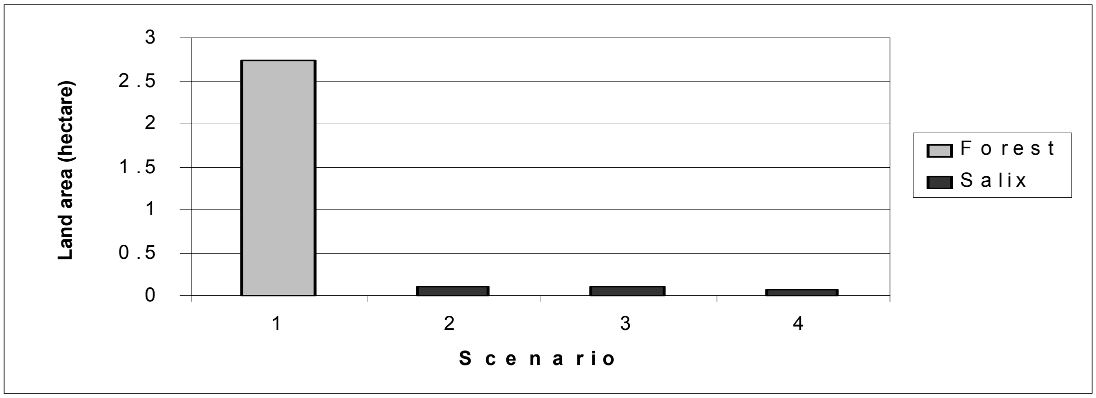

Fig. 9. Results of land use requirements (hectare) per 1 MWh electricity generated.

5.4. Critical Discussion

The substantial decreases in fossil fuel use, CO_2 emissions, and land use indicate that the alternative Salix, bio-fertilizer, and gasification sub-system proposals provide increased efficiency to biomass energy systems. The Salix and bio-fertilizer sub-systems have been presented as theoretically beneficial to the environment but few studies have determined whether these changes actually decrease the energy, material, and emissions.

The results of this study prove that interrelationships expressed in Fig. 4 are valid. Substantial efficiency improvements of the alternative sub-systems allow the bio-energy system loop to increase biomass electricity production. The increased development of biomass energy forms a reinforcing relationship because alternative development measures decrease the limiting variables fossil fuel use, CO_2 emissions, and land use. This reinforcing relationship is dependent upon the supply of land, however increased efficiency of Salix production in the future should limit land conflicts between food and energy crops. Establishing an efficient biomass system with the addition of Salix, bio-fertilizer, and gasification technologies can ultimately decrease the world's dependence on fossil fuels and lower global warming.

The inherent limitation of this study is the accuracy of the LCI data (appendix 2) that influence the outcome of the modeling efforts. However, every effort has been made to ensure that the data is accurate and the scenario results provide valuable information. Several other scenarios could have been designed to illustrate partial adoption of alternative subsystems, however the overall trends are clearly described by the scenarios chosen for this study.

6. Conclusions

This study revealed that alternative subsystems such as Salix biomass, bio-recycled fertilization, and gasification technology greatly increase the overall efficiency and sustainability of the biomass energy system. By implementing these subsystems, levels of fossil fuel input and CO_2 emissions were reduced by 74 percent and land requirements were reduced by 97 percent. Reduced energy requirements, reduced system emissions, and reduced land requirements increase the overall efficiency of the biomass energy system and thus increases the development potential of improved integrated biomass energy systems.

Energy futures are strongly linked to social and environmental futures. Poor energy planning risks the inevitable loss of life in environmental disasters, risks the money sunk into fossil fuel dependent energy systems, and ultimately risks the long term future of humanity. The energy industry must pay greater attention to the enormous liability they face when society finally faces the enormous social, environmental, and ultimately economic devastation caused by intense fossil fuel use.

Energy planners must recognize the role bioenergy plays in meeting the additional energy needs of the world while honoring the growing social and environmental requirements of future energy systems. This study demonstrated that an improved biomass energy system dramatically increases efficiency and sustainability in an effort to make biomass development synonymous with future energy development.

This thesis research could lead to several future applications. Similar assessments of other energy production methods such as solar, wind, coal, and nuclear could be analyzed against this study to determine the comparative advantages or disadvantages. Absolute and indirect economic data of improved biomass energy systems could be combined with this study to determine a cost benefit analysis report of biomass energy systems. This type of study would prove valuable in presenting government and energy business leaders with the social, environmental, and economic benefits of integrated biomass energy systems.

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Appendix #1: Life Cycle Assessment – an Overview and methodology

1. Definition

The complexity of identifying environmental pollution sources and the magnitude of complex pollution effects on the international community demands a broader focus. Previously, product and process analysis simply included the production and generation of products and energy at local point source. However, in order to evaluate the increasing complex environmental impacts of internationally produced and traded goods, it necessary to assess the whole chain; from the extraction of raw materials to the end use consumer.

Industry, government, and consumers face an important paradigm shift. They must realize that every activity is actually supported by a complex system. This holistic 'systems' perspective integrates the different steps into a single larger frame, producing a clearer picture of the impacts along the process. This 'systems thinking' has evolved into a new practice of life-cycle assessments.

Industry is gradually adopting the LCA concept as a means of understanding, managing, and reducing the environmental, health, and resource consumption impacts of its industrial processes, products, and activities. Realizing the importance of evaluating and improving the environmental quality of its products is an important step towards the development of sustainable business practices [51]. Sustainable business philosophy is not only important for balancing the impacts on the environment by improving efficiency but LCA thinking helps business improve its fundaments, 'bottom-line', and reduce risks.

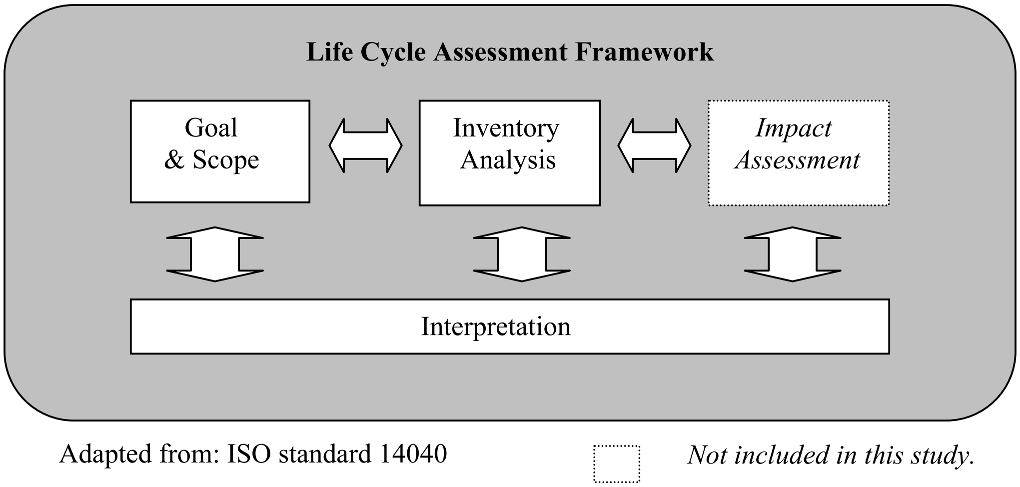
Life-Cycle Assessment can be described as a disciplined thinking process applied to different levels of a system [51]:

- Conceptually as a thought process that guides the selection of options for design and improvement,
- A qualitative assessment building on key environmental burdens or release at stages in the life-cycle of a product, or,
- Methodologically building on a quantitative inventory of environmental burdens or releases, evaluating the impacts of those burdens or releases, and considering alternatives to improve environmental performance

Life-Cycle Assessment (LCA) is both a concept and methodology for auditing and evaluating environmental performance of products, processes, and activities over their entire lifetime 'from cradle to grave'. The aim of this holistic approach is to identify and quantify all factors/variables in the system relevant to resource consumption and environmental impact. The entire life cycle includes crude material extraction, manufacturing, transport and distribution, product use, service and maintenance, recycling and final waste handling. In order to assess the energy and environmental expenses along the life cycle chain, a mathematical computer model is designed to show a representative picture of the environmental impacts of the real system.

The model is representative of the real system to the extent that the various approximations and assumptions in the model depict the real thing. Complex systems with multiple interactions between different parts, such as production processes, can be studied using the LCA methodology. A picture of the system can allow for possible evaluation of the environmental impacts of the system based upon the ecological effects and resource use. An LCA usually does not directly include an evaluation of the economic and social effects of a system.

A LCA is generally divided into three basic steps. The first two steps have a well-established methodology that results in a life-cycle inventory (LCI), while the third more difficult step is the impact assessment. The LCI portion of the study can be performed and reveal much about the studied system exclusive of the third step. Interpretation is often an important element at all steps of a study. The three basic steps are presented below in Fig. 10.



Adapted from: ISO standard 14040

Fig. 10. Principles and framework of life cycle assessment environmental management [52].

2. Functional unit

The functional unit of the system is the measure of performance delivered by the system. Therefore the functional unit is a well-defined strict measure of the analyzed function that the system delivers. The functional unit should be clearly defined and measurable so that it is possible to relate the relevant input and output data. The functional unit is usually given by the definition of the function of the system. In summary, the functional unit(s) of the studied system(s) should properly describe the services provided and be clearly defined and reported [51].

3. Goal definition and scope

The ‘goal definition and scope’ component of a LCA is one of the most critical parts of the study. The objective of this section is to present a clear understanding of the purpose, the studied system(s) and the intended application including limitations. The minimum decisions and definitions that need to be made in the ‘goal and scope’ phase are: the purpose and intended application, the function of the studied system(s) and defined functional unit, the system boundaries, defining the data quality and quality assurance of the study [51]. Life cycle boundaries relate to where up-stream, down-stream and side-stream cut-offs are set for detailed subsystems inside the system boundaries. The goal and scope definition sets the boundaries of the study, allowing the analysis and assessment of the system to subsequently take place.

4. Inventory Analysis

The inventory analysis is the heart of the modeling effort including the material and energy flows, which are quantified as best as possible. The flows have several subsystems such as crude material extraction, refining, transport, production, that collectively describe the system. These subsystems have quantified variables that seek to describe the activity or process described in that subsystem. The subsystems are then linked together with the appropriate relationships to describe the system within the prescribed system boundaries. The actual analysis of the inventory assessment takes place when the completed model is set to calculate the different variables per functional unit of the entire system.

Appendix #2: Life Cycle Inventory Data

In this section, the LCI data for the different processes such as diesel fuel production, conventional fertilizer production, biological fertilizer production, production of biomass fuel, and production of CHP energy are presented. These processes are the building blocks that define the LCI biomass model. Each process involves flows of energy, materials, and emissions. These flows are calculated in each process per its own function unit, e.g. per MJ diesel produced, per ton fertilizer production, or per MWh electricity produced.

1. Diesel fuel production

The production data for diesel fuel includes the extraction, refining and transport of the diesel oil to the consumer. This part of the fuel chain is often described by so called ‘precombustion’ factors. Basic data for extraction and transports are derived from the study, “Life Cycle Data for Norwegian Oil and Gas” [53] supplemented with data for steel production of 25% virgin and 75% recycled steel [54]. The drill platform uses no external electricity. The consumption of crude oil is recalculated to MJ using the lower heating value of 42.7 MJ/kg. The refinery data are from a Norwegian refinery. Average data for other production sources are expected to be higher, due to less efficient production measures. Precombustion data can vary significantly between different LCA studies; therefore, this data must be considered as relatively uncertain.

Table 2. LCI data for production of diesel fuel, as used in model.

Substance	Value	Unit
Energy Input		
Fossil oil	1.1	MJ
Emissions		
CO_2	0.00322	kg
NO_x	0.00005	kg
SO_2	0.0000036	kg
Particles	0.00000000886	kg
Energy fuels		
Diesel fuel oil	1	MJ

2. Combustion of Diesel for biomass production

These two modules calculate the fossil fuel energy and emissions per hectare of forest and Salix operations. The LCI data for these modules is located in the “Forest-residue & Salix chip production” discussion in a later section.

3. Transport – heavy truck

Life cycle inventory data for transport is included in this study. The transport is indicated by a hash mark on the KCL-ECO flow arrows in Fig. 5. A 1995 large 20 ton long distance truck with a load capacity of 40 tons was assumed to be the transport of choice in biomass production applications. It was also assumed that the weight not the volume is the limiting factor for the load capacity, i.e. the truck can be loaded to a maximum weight.

In the life cycle calculations of this module, the low sulfur (city diesel) fuel consumption of the truck was considered. The production of the diesel fuel, precombustion data, is included in this module. However, the production and maintenance of the truck is not included in this study. To avoid differences between different truck manufacturers, the 1995 EU regulation for diesel truck emissions was used to generate the data in the table below [55]. The transport distance is 70 kilometers [37,56].

Table 3. LCI data for transportation of 1 ton, 1 kilometer

Substance	Value	Unit
Input Resources		
Crude oil	0.4	MJ
Emissions		
CO_2	0.0294	kg
NO_x	0.00029	kg
SO_2	0.0000236	kg
Particles	0.000012	kg
Output: transportation		
Transportation	1	ton-km

3. Production of Conventional Fertilizers

Nitrogen, phosphorus, potassium and lime are conventional agricultural fertilizers. Their production requires much fossil energy as illustrated in the following descriptions and tables [32,57].

3.1. Production of Nitrogen fertilizer

The LCI of nitrogen production reveals that it is one of the most energy intensive fertilizers.

Table 4. LCI data for production of kilogram nitrogen.

Substance	Value	Unit
Energy		
Fossil fuel (oil)	2.16	MJ
Electric power	38.88	MJ
Natural gas	2.16	MJ
Emissions		
CO_2	2.641	kg
NO_x	0.002484	kg
SO_2	0.0009374	kg
Particles	0.001581	kg
Materials/products		
Nitrogen fertilizer	1	kg

3.2. Production of Potassium fertilizer

Table 5. LCI data for production of kilogram potassium fertilizer.

Substance	Value	Unit
Energy		
Fossil fuel (oil)	1.41	MJ
Electric power	2.115	MJ
Natural gas	1.175	MJ
Emissions		
CO_2	0.4656	kg
NO_x	0.0008772	kg
SO_2	0.0004312	kg
Particles	0.001439	kg
Material/products		
Potassium fertilizer	1	kg

3.3. Production of Phosphorus fertilizer

Table 6. LCI data for production of kilogram phosphorus.

Substance	Value	Unit
Energy		
Fossil fuel (oil)	2.04	MJ
Electric power	3.06	MJ
Natural gas	1.70	MJ
Emissions		
CO_2	0.6735	kg
NO_x	0.001327	kg
SO_2	0.002082	kg
Particles	0.0006239	kg
Material/products		
Phosphorus fertilizer	1	kg

3.4. Production of Lime

Lime is commonly used to raise the pH of soils to the optimal level for certain plant growth. In thin soils with minimal limestone base, such as those in Sweden, acidification is counter measured by the addition of lime to the soils. Depending on the pH of the soil, lime or an equivalent liming agent may or may not be necessary to add. In this model it is assumed that liming is needed to achieve proper biomass growth.

The LCI data for lime production is calculated from information from a producer. The data include material extraction, grinding and transportation to a central distribution point [58]. Data are calculated from resource extraction to factory gate.

Table 7. LCI data for production of kg limestone [58].

Substance	Value	Unit
Energy Input		
Fossil fuel (oil)	0.023	MJ/kg
Electric power	0.22	MJ/kg
Emissions		
CO_2	0.0079	kg
NO_x	0.000031	kg
SO_2	0.00004	kg
Particles	0.000021	kg
Materials/products		
Lime production	1	kg

4. Alternative Liming and Fertilizer production

There are alternatives to conventional lime and fertilizer production. The first option, ash and lime mixture, was researched in an effort to recycle the ash generated from the power facilities and avoid waste landfill fees. Depending on the set-up of the boiler and the temperature of the burn, determines whether the bottom or fly ash is chosen for processing.

The Enköping facility in this study operates a steam boiler with natural circulation and equipped with a water-cooled vibration grate. This facility set-up concentrates any heavy metals in the fly ash. Therefore, the bottom ash is chosen for recycling and the fly ash is stored awaiting further action.[19]

The energy from this mixing process is provided in the form of diesel fuel and produces emissions, all of which are detailed in Tables 8 and 9.

4.1. Ash and Lime fertilizer mixture

A lime & bottom ash mix was proposed as an alternative to 100 percent lime for the forests. As Table 8 illustrates 1/3 of the lime is substituted with unprocessed bottom bio-ash. The two components are then mixed and ground into spreadable pellets.

Table 8. LCI data for production of BioAsh & Lime mix : mixing and crushing [56,59].

Substance	**Value**	**Unit**
Materials/products		
Lime	607	kg
Unprocessed BioAsh	303	kg
Energy		
Fossil fuel (diesel)	2.99	MJ
Emissions		
CO_2	0.225	kg
NO_x	0.00306	kg
SO_2	0.00018	kg
Particles	0.000072	kg
Materials/products		
Processed Ash/Lime	1000	kg

4.2. Sewage Sludge and Ash fertilizer mixture

In the second alternative, sewage sludge and bottom ash are mixed together to form an alternative liming and fertilizer agent for the Salix fields. This option was not used in the forest because of questions regarding the affects of nitrogen and other components of the sludge on the forest ecology. The sludge is mixed with the bottom ash in 50:50 proportions as illustrated in Table 9.

This module is added in an effort to recycle the ash generated from burning the biomass and recycle the sewage sludge from a local municipality. The nutrients from both sources are vital for plant growth and replace the use of synthetic fertilizers. This operation is presently under operation and research at the Enköping CHP facility.

The preparation of the fertilizer involves mixing the sludge and bottom ash in a 50:50 proportion, allowing it to "set", and then crushing it into a homogenous consistency. LCI energy use data for this process was adapted from the Nässjo ash processing facility, which mixes ash with water and crushes [56,59].

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[19] Presently the contaminated fly ash is properly stored in conventional means, such as a landfill. However, in the future the heavy metals may be extracted and recycled back to appropriate industries.

Table 9. LCI data for production of sludge and ash fertilizer: mixing and crushing [56,59].

Substance	Value	Unit
Materials/products		
Digested Sludge	500	kg
Unprocessed BioAsh	500	kg
Energy		
Fossil fuel (diesel)	2.99	MJ
Emissions		
CO_2	0.225	kg
NO_x	0.00306	kg
SO_2	0.00018	kg
Particles	0.000072	kg
Materials/products		
Processed BioAsh	1000	kg

5. PRODUCTION OF BIOMASS FUEL

The two primary sources of biomass fuels, forest-residue chips and Salix chips. The following two sections present the flows through forest-residue and Salix chip production. The primary flow being the amount of diesel fuel needed to process each hectare and the subsequent biomass output per processed hectare.

5.1. Production of Forest-residue chips

The diesel energy used per hectare of forest residue production was calculated from averaging the fossil energy input values from the following operations: after final felling and first thinning [32].

Intensive utilization of forest-residues requires at least the addition of conventional lime to stabilize the pH of the forest soils. Lime is twice as effective as wood-ash in lowering the pH; therefore, half the amount of wood-ash proposed by Börjesson was calculated as sufficient lime [32].

The processed bio-ash was an alternative to the conventional lime. 3000 kg per hectare wood-ash is needed to compensate the nutrient losses from roundwood and forest-residue harvest. Calculated on an 80-year harvest cycle, 3000 kg was divided by 80 to receive 37.5-kg wood-ash per ha per year.

The amount of forest-residue chips produced was calculated by averaging the yields of final felling and first thinning and adding about 35 percent moisture content to simulate fresh collection.

Table 10. LCI data for production of forest residue chips: from collection to processed chips [32,59]

Substance	Value	Unit
Materials/products		
Lime	19[1]	kg
(or) Processed Bio-Ash	37.5[2]	kg
Energy		
Fossil fuel (diesel)	260	MJ
Emissions		
CO_2	19.5	kg
NO_x	0.2652	kg
SO_2	0.00624	kg
Particles	0.0156	kg
Energy resources-renewable		
Forest-residue collection	1	hectare
Forest-residue chips	513	kg

[1] Conventional scenario / [2] Alternative scenario

5.2. Production of Salix Chips

The data below in Table 11 illustrates the flows through Salix farming. The farming of Salix is described by the 'comb diesel: Salix farming' and the 'Salix farming chips' modules combined. The operation was separated in order satisfy the operation of the model, by assigning the flows per function unit.

The module's output of Salix chips is based upon 9.3 odt[20] ha^{-1} $year^{-1}$ production data from Börjesson [32]. At the time of harvest the 50 percent moisture content of the chips adds 50 percent more weight to the output value, 9.3 odt. Therefore, approximately 14,000 kg of fresh Salix chips are produced per hectare per year in established fields.

Table 11. LCI data for the production of Salix chips on 1 hectare: from farming to harvesting [32,59]

Substance	Value	Unit
Input:		
Fossil fuel (diesel)	2100	MJ
Materials/products		
Lime	37.5[1]	kg
Nitrogen	81[1]	kg
Phosphorus	11[1]	kg
Potassium	29[1]	kg
(or) Processed Bio-Ash	480[2]	kg
Output Emissions		
CO_2	157.5	kg
NO_x	2.142	kg
SO_2	0.0504	kg
Particles	0.126	kg
Energy resources-renewable		
Salix farm	1	hectare
Salix chips	14000	kg

[1] *Conventional scenario* / [2] Alternative scenario

6. Production of Biomass Energy

6.1. Production of combined heat and electric power (CHP)

The LCI data for this module was calculated from 1999 operation information at Enköping [37].
350 GWh of bioenergy is used annually by the CHP facility, of which 200 GWh is useful heat production in CHP and 70 GWh is net electrical output on the grid [37]. Biomass is consumed at an annually rate of 9,000,000 kg releasing emissions [37]. For purposes of the model, these values were calculated in kg per generated MJ energy by converting units and dividing by the total generated energy in MJ as shown in Table 12 below.

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[20] 9.3 odt Salix chips per hectare per year is a low average. Field trials by farmers in Sweden have achieved total above-ground yields of 10 to 12 odt per hectare per year [60]

The LCI data 'biomass LHV' was calculated from the following Equation 1. The equation is from an engineering book and the variable values are noted below after the equation.

Equation 1[61]: LHV = [1]HHV*(1-moisture content) – [2]hydrogen content of fuel* 22.0(1-moisture content of fuel-elemental ash content) – [3]moisture content*2.45.

HHV = 20 MJ/kg [32,22,62]
moisture content = 0.35
hydrogen content in fuel = 0.06 [61]
elemental ash content=0.01 [58,63]

[1] Proportion of the wood fuel that is water.
[2] Energy to evaporate the water formed when the H in the wood fuel forms water.
[3] Energy needed to evaporate off the water.

The values of the variables: 'biomass LHV' and 'overall efficiency'; can be easily adjusted in the model to allow for scenario development.

Table 12. Selected LCI data for the production of 1 MJ electric and heat energy, CHP.

Substance	Value	Unit
Input renewable fuel		
Biochips[1]		kg
Bio-energy (MJ)[3]	*(Biomass LHV[2] * Biochips)*	
Emissions[4]		
CO_2	0	kg/MJ
NO_x	0.00005	kg/MJ
SO_2	0	kg/MJ
Particles	0.000001	kg/MJ
Unprocessed Ash[5]	(0.03 * Biochips kg)	
CHP Energy	(Bio-energy * overall efficiency[6])	

[1] Biochip flow determined by the equation: Bio-energy (MJ) = Biomass LHV (MJ/kg)* Biochips (kg).
[2] 11.5 MJ/kg -- Lower heating value (LHV) of biomass feedstock calculated from Equation 1 and from solving for an unknown variable in the model.
[3] Bio-energy represents the MJ of energy present in the biomass fuel
[4] Emissions calculated per MJ produced CHP energy [49]
[5] Calculated that about 3 percent biomass ended up as ash [64]
[6] Overall efficiency, 77%, is defined as the energy input, bio-energy (MJ), compared to the useful CHP output (MJ) [43]

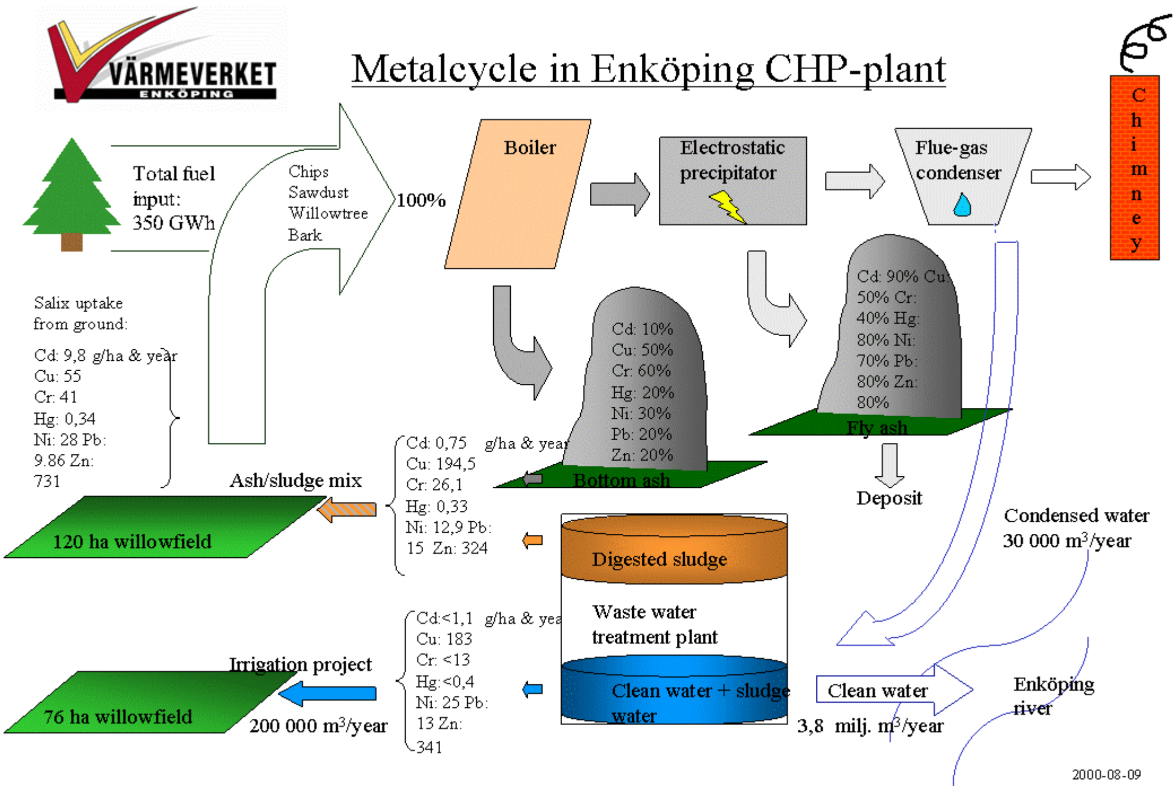
6.2. Electricity Production

Electricity is produced from the steam produced in the boiler. The steam propels a conventional steam turbine. The efficiency of turning steam energy into electrical energy in these turbines is usually in the low to mid twenty percent. In this model, the Enköping facility had about 26 percent electricity generation efficiency.

The final module in Fig. 5 calculates the electricity output by multiplying the electrical efficiency by the total heat energy generated. The electrical energy is finally converted from MJ to MWH by multiplying by the conversion factor 3600 MJ per 1 MWh.

The values of the variables: 'electrical generation efficiency' and 'electricity output'; can be easily adjusted in the model to allow for scenario development.

Appendix #3: Diagram of Metal flows through Enköping Facility



Additional Reading

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The World Bank – the economic development institute. 1991. Morris Miller. Sustainability and the Energy/Environment Connection: overcoming institutional barriers to "doing the right thing". EDI Catalog No.: 251/029. Washington D.C. 202-473-6351.

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Reinventing Electric Utilities: competition, citizen action, and clean power. Ed Smeloff and Peter Asmus, 1997. Safe Energy Communication Council. Island Press. ISBN 1-55963-455-3.

Robert Hill. The future of energy use. ISBN 1 85383 107 7. benefits of biomass: CO2, rural development, desertification, forest fires, social/political (pages 156-161) "Energy futures can reasonably be considered as environmental futures. At a time when bad energy planning and provisions can easily be seen to have cost lives and money, and to have risked the long term future of humanity, it is of paramount importance that energy policies reflect the shifting requirements of environmental and social sustainability. The world's energy industries must pay greater attention to the endorse requirements of individuals rather than to the mere provision of historically projected trends. The challenge is to create the society we want rather to predict the society we will have." (page 177)

Understanding the overall pros and cons of various long term energy development options challenges energy developers and investors to reconsider renewable energy sources such as biomass as an efficient fuel source that lowers their risky relience on fossil fuels and

The breadth of this type of research underscores the fact that energy systems are long term development projects that deserve intense long term analysis.

Therefore, the efficiency and sustainability of biomass energy systems can be greatly enhanced and more competitive in the changing energy market.