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Analysis of Limiting Factors for Life Cycle Assessment of Biomass Energy Systems

Alireza Kiaee

Mechanical Department, K. N. Toosi University of Technology, Tehran, Iran

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ABSTRACT

Background: 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 research 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 CO2 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 CO2 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.

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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 (Geppert and Perry, 2000).

In the last decade, deregulation and technological development in the electrical industry have increased the potential development of renewable energy systems1. 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 (Givargis *et al*., 2000).

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. 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. 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.

Corresponding Author: Alireza Kiaee, Mechanical Department, K.N. Toosi University of Technology, Tehran, Iran
E-mail: kiaeealireza@chmail.ir

Journal of Applied Science and Agriculture, 9(9) July 2014, Pages: 35-42

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, biorecycled fertilization, and gasification technology affect the net efficiency of the biomass energy system. 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.

Literature review:

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.

Increasing World Electricity Demand:

Worldwide electricity consumption in 2020 is projected to substantially increase 76 percent over 1997 levels (Quinn, 2000). 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. The substantial increase in electricity production around the world will contribute further to global CO2 , SOx , and NOx 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.

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 (Jenkins, 1989).

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.

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 greatest potential for micropower may lie in providing reliable access to electricity for over 3 billion individuals in developing countries (Midttun, 1995). 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. 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. 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 with micropower systems such as biomass.

Global Warming:

Greenhouse gases such as carbon dioxide prevent heat from leaving the earth, therefore warming the earth's atmosphere. Emissions of CO2 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 CO2 from the USA is produced from power facilities, therefore connecting power system development and the issue of 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 CO2, methane (CH4), and nitrous oxide (N2O). GHGs trap heat radiation and inhibit its release back into space, thus, leading to the global climate change. Human activities such as electricity production lead to the increasing GHG levels.

"CO2 and methane (CH4) are two of the most potent gases that contribute to global warming. Fossil fuels are major contributors to global warming, producing large amounts of CO2". Burning biomass emits CO2 but renewably grown biomass leads to a net zero increase in atmospheric CO2, because reestablished trees absorb the biogenic CO2 released during biomass combustion.

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 CO2 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 CO2 concentration3 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.

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 NorthAmerica 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". 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. 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 CO2 concentration in the atmosphere by reducing the fossil fuel based electricity production and providing a medium to sequester CO2 in unused biomass crops.

In order to decrease the effects of global warming caused by increased greenhouse gases such as CO2, biomass renewable energy systems are receiving renewed development attention. The subsystems associated with biomass development are also explained. Biomass is defined as organic matter, such as wood, crops, and animal wastes. Solar energy powers photosynresearch, which stores that energy in the form of plant matter. Therefore, biomass is stored solar energy.

Photosynresearch 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 (Catthoor, 2000).

Because biomass is a solid fuel, comparisons between the properties of biomass and coal are instructive. On a dry-weight basis, heating values4 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. 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 wood5 in contrast to the moisture content of most bituminous coals ranging from 2 to 12 percent. 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 (SO2) emissions (EPA, 2000). Therefore, biomass energy systems help alleviate acidification.

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.

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.

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 (SRC) willow plantations. 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.

MATERIAL AND METHODS

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, 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. 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 (Chandrakasan, 1996).

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

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. 1 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 Iran. The operations at this facility direct firing facility are probably more efficient than the global average. As Fig. 1 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. 1 illustrates the parts of the system covered in this study.

Journal of Applied Science and Agriculture, 9(9) July 2014, Pages: 35-42

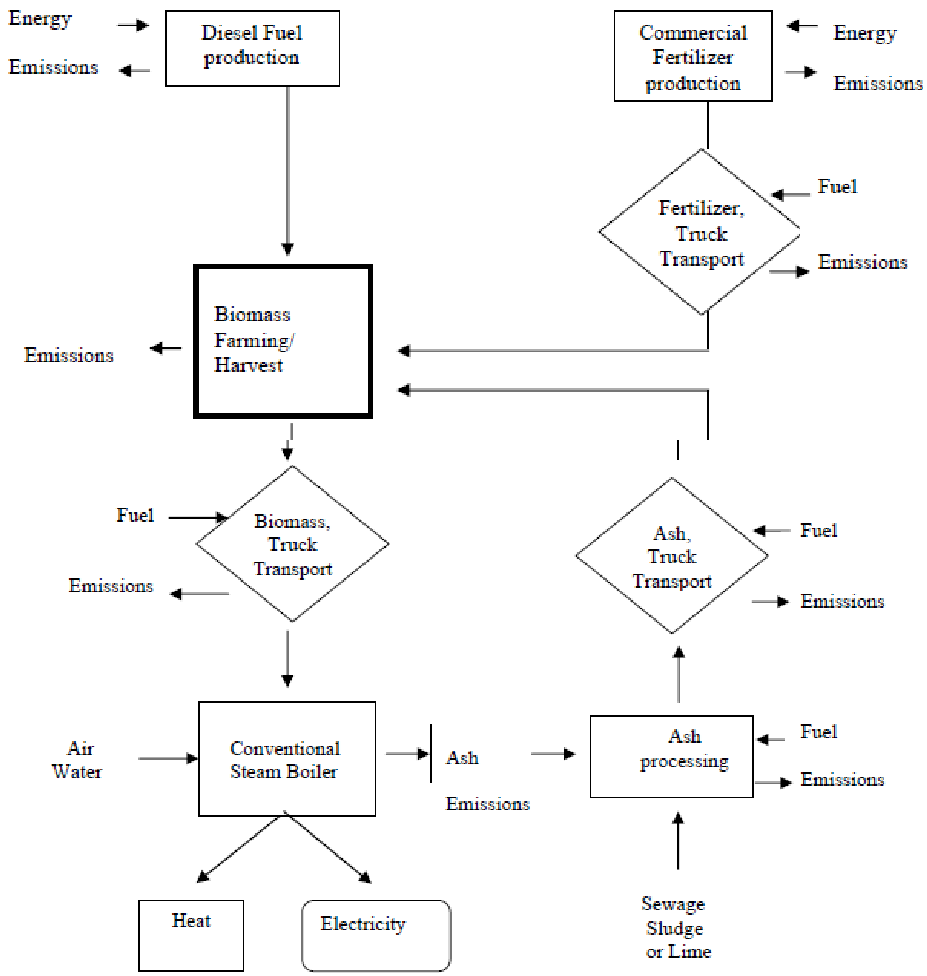

Fig. 1: Flowchart showing the life cycle of biomass production and heat & electricity energy.

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

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 Iran, 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.

Industry data:

Data on fuel and emissions for 1999 was requested and analyzed from three biomass facilities in Iran. 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.

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 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. Fig. 2 illustrates the final model that was creasted in KCL-ECO to represent the life cycle of biomass production.

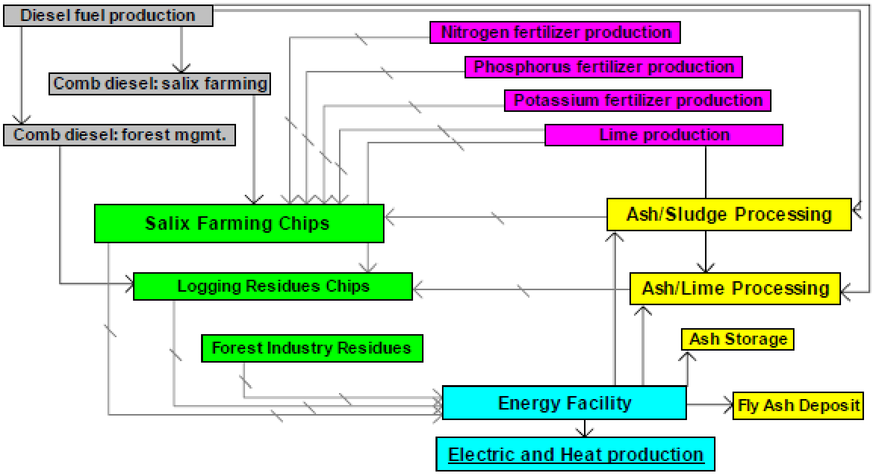

Fig. 2: KCL-ECO flowsheet of the LCI modules.

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 Iran by modifying the boiler to achieve 100 percent Salix chip input (Alexander, 2009).

As Fig. 2 illustrates, the corresponding support systems that ensure that the biomass fuel reaches the energy facility are interconnected with the inner model data explained. 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.

RESULT AND DISCUSSION

In the interest of testing the hyporesearch 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.

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. 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', 'CO2 emissions', and 'land use' variables were chosen to reveal the overall efficiency of the biomass system.

Fossil energy combustion produces CO2 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), CO2 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%

Conclusion:

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 Iran and around the world. Iran utilizes biomass to meet around 19 percent of its energy needs. Biomass has been so successful in Iran because the limiting factors are minimized by a large forest industry and small concentrated towns that can efficiently use the excess heat. However in Iran, 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, CO2 emissions, and land use variables represent limiting factors that must be decreased to improve efficiency and the degree of sustainability.

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 CO2 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

Journal of Applied Science and Agriculture, 9(9) July 2014, Pages: 35-42

dramatically increases efficiency and sustainability in an effort to make biomass development synonymous with future energy development.

This research 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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