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PRELIMINARY CHARACTERIZATION OF TASE BIOMASS TECHNOLOGIES

by

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ABSTRACT

In 1978, the U.S. Department of Energy initiated the TASE (Technology Assessment of Solar Energy) Program to assess the environmental consequences of increased utilization of solar energy. An overview of the TASE Program and a discussion of the biomass technologies characterized in Phase I will be presented in this paper. Appropriate biomass conversion technologies were selected for various biomass feedstocks (i.e., agricultural and forestry residues, municipal wastes, manures, and agricultural and forestry energy crops). The technology characterization process involved: description of a model system; input/output analysis of material and energy flows into the system; estimation of the amount of residuals (e.g., particulates, SO_x, etc.) generated during conversion; and estimation of capital and operating and maintenance costs for each system. Results were computed on a per Quad (10^{15} Btu) basis and coded for input into the SEAS (Strategic Environmental Assessment System) model. This discussion of the TASE biomass technology characterizations focuses on agricultural residues, forestry industry residues, and livestock wastes.

INTRODUCTION

Solar energy technologies have recently become a focus of intense research and development not only because of their potential for replacing conventional nonrenewable energy resources but also because they are generally perceived to be relatively benign in terms of environmental and socioeconomic impacts. However, the use of solar technologies is not without externalities, especially when construction, material supply, employment requirements, and other secondary or indirect impacts are considered. The potential environmental and socioeconomic impacts, both positive and negative, resulting from a widespread application of solar energy technologies have not been adequately addressed in the past. Accordingly, the Office of the Assistant Secretary for Environment of the Department of Energy has initiated the Technology Assessment of Solar Energy (TASE) Program.

The purposes of the TASE Program are to examine on a national, regional, and community level the nature of the environmental and socioeconomic impacts likely to result from widespread use of solar energy technologies; to identify the potential for substituting solar technologies for conventional sources as a strategy for mitigating energy-related environmental and socioeconomic problems; to identify physical, environmental, and institutional factors that may limit the substitution of solar energy for energy from conventional sources; and to identify regional variations that may facilitiate development and use of particular combinations of solar technologies.

The TASE Program has two phases. Phase I provides a preliminary evaluation of the generic environmental impacts of solar energy technologies. Phase II of the TASE Program will draw upon the results and analysis of the Phase I effort to assess the environmental consequences of a national deployment of solar energy technologies.

One primary objective of the Phase I activity is to evaluate, on a per Quad (10^{15} Btu) basis, the amount of environmental residuals and the costs (capital, operating, and maintenance) of each solar technology system, from raw material extraction to end use. Results of these evaluations are the subject of this paper.

Additional objectives of the Phase I program are to determine, by means of an input/output analysis of selected solar demand scenarios, the raw materials and resources needed to manufacture and operate the solar and any ancillary systems; to examine the ability of communities to assimilate into their physical, social, and institutional structures increasing quantities of solar-derived energy; to assess the environmental and institutional impacts of solar energy use on spatially constrained communities; and to examine the environmental and institutional character of a community, under varying solar growth assumptions.

These objectives provide a basis for moving from generic assessment of impacts to the Phase II assessment that considers specifics of national and regional resource usage, cumulative environmental impacts, socioeconomic impacts, and institutional uncertainties. As a basis for the Phase II analysis, two national scenarios for level of solar deployment in the year 2000 are specified: a scenario with a high level of solar penetration similar to the Domestic Policy Review "maximum practical" scenario and a second scenario with lower penetration, assuming a general continuation of current energy policies. The Phase II assessments are being conducted jointly by the DOE and the Argonne, Brookhaven, Lawrence Berkeley, Los Alamos, Oak Ridge, and Pacific Northwest/Battelle Laboratories, with support from DOE's Division of Technology Assessment and MITRE Corporation.

TASE Phase I Approach

The broad scope of Phase I of the TASE Program necessitated a division of the tasks required to effect the study. Eight technologies were selected for study, including some non-solar decentralized types. Los Alamos was primarily responsible for heating and cooling, agricultural and process heat, photovoltaics, and wind technologies. SERI, MITRE Corporation, and Lawrence Berkeley Laboratory also developed characterizations for these solar technologies. Argonne and Oak Ridge were assigned biomass technologies. Lawrence Berkeley was responsible for cogeneration and waste combustion. Oak Ridge was additionally responsible for district heating. The biomass technology was divided on the basis of resources; Argonne was to identify appropriate applications for crop and forestry residues, livestock wastes, and sewage while Oak Ridge was to define terrestrial energy crop applications.

Thus, Argonne's assignment for biomass technologies during Phase I was to identify end-use energy applications for various biomass resources. Upon selection of a biomass conversion application, the following tasks had to be performed to characterize the chosen system:

A technical description of the model system and the amount of end-use energy supplied;

An input/output analysis of material and energy requirements of the model system per Quad of end-use energy;

An assessment of the system's capital costs and operating and maintenance costs per Quad of end-use energy; and

An assessment of operating residuals (e.g., pollutants) generated by the system per Quad of end-use energy.

The capital and operating costs were identified for each industrial sector in which expenditures were made. This allowed inferences as to the basic raw material requirements for the application.

The integrating factor in the study is SEAS (Strategic Environmental Assessment System) (House, 1977). This model permitted the integration of the technology characterization data being developed at the various national laboratories and other institutions, so that the national, regional, environmental, material, energy, and economic objectives are achievable.

SEAS is an extremely intricate system. Basically, SEAS is a set of interrelated computer programs that can model energy flows in the U.S., model the U.S. economy, calculate environmental pollutants, and provide these energy, economic, and environmental forecasts at the national and various regional levels. Thus, in TASE Phase I the microlevel work on solar energy systems is melded via SEAS into macrolevel forecasts.

The remainder of this paper will be on selected biomass technology applications studied at Argonne National Laboratory. This will provide a representative perspective on the microlevel input for biomass technologies into the SEAS model. Because of space limitations, an adequate definition of all the assumptions and perspectives of our work is not possible and the readers are referred to forthcoming project reports; one deals with agricultural and forestry residue applications (Harper et al., 1979) and the other with livestock wastes and sewage (Ballou et al., 1979). These biomass technology applications will be presented for agricultural residues, livestock wastes, and forest industry residues in this paper.

AGRICULTURAL RESIDUE APPLICATIONS

General Soil Effects

Perhaps one of the most significant environmental effects of using agricultural residues for energy is the deterioration of the soil by the erosive forces of water and wind. It has been reported that runoff almost doubles when crop residues were removed (Brady, 1974). The raindrop effect destroys surface soil structure, causing puddling, decreased water infiltration, increased runoff, reduced porosity, increased soil compaction, and a loss of organic matter and plant nutrients. In the semiarid wheat and cotton growing areas, the wind sorts the dry surface soil material by blowing away the fines, leaving only the semi-sterile skeletal matter (Lyles, 1975). This fine soil material contains a high portion of nutrients that are readily available to plants, and some experiments have shown eroded sediment to contain five times more organic matter and nutrients than the original soil.

Another major loss of soil nutrients is in removal of the residues themselves. Table 1 lists the amounts of major soil nutrients (nitrogen, phosphorus, and potassium) removed with corn, wheat, and cotton residues.

Table 1. Major Soil Nutrients Removed With Crop Residues

Crop	Nitrogen (lb/ton residue)	Phosphorus (lb/ton residue)	Potassium (lb/ton residue)
Corn Residue	22.2	3.6	26.8
Wheat Residue	6.0	0.5	8.9
Cotton Residue	34.8	4.5	29.4

Thus, the nutrients are often removed in excess of those applied, and the difference comes from the reserve previously built up in the soil. These nutrients must be maintained. Therefore, the total nutrients removed in the residue should be accounted for in the amount of fertilizer applied with the next corn crop to mitigate the adverse consequences of soil deterioration. In the analyses of technologies, the land areas temporary affected by residue removal and the additional fertilizer requirement have been incorporated into the analysis of the various crop residue systems.

Combustion of Cotton Ginning Residue

Ginning of cotton produced in the U.S. gives rise to three distinct products: lint (cotton fibers), cottonseed, and ginning residues which consist of leaves, sticks, stems, hulls, soil, and motes (Griffin, 1976)(Oursbourn et al., 1978). Residue production per bale ranges from 98 lb for spindle-harvested mid-south cotton to approximately 750 lb for Texas stripper-harvested cotton (Griffin, 1977).

The seed cotton at the plant must be dried before it can be ginned. Typically 430,000 Btu per bale (Holder and McCaskill, 1963) are required for drying. Recently, drying systems have been developed that use cotton ginning residue as a fuel instead of natural gas for drying the seed cotton. The mean dry-basis fuel value of cotton gin residues is 7032 Btu/lb.

The designs of systems for recovering gin residue and incinerating it to provide energy for drying have been reported by several authors (Lalor et al., 1976) (McCaskill and Wesley, 1976) (McCaskill et al., 1977). Researchers at the U.S. Cotton Ginning Research Laboratory have developed a system with 30% heat exchanger efficiency (McCaskill and Wesley, 1976). This system provided sufficient heat recovery for processing rates from 6 to 30 bales per hour, which spans production capacities for most cotton gins in the U.S.

For this study, the model system proposed for seed cotton drying proposed is simple: it consists of three basic operations, separation, combustion, and heat transfer. The model system does not have a gas scrubber on the incinerator so that a worst-case residual estimate is used to evaluate the conversion technology. The capacity of the system is 20,000 bales per year.

Based upon one-Quad output of useful process heat from the system (i.e., replacing natural gas), the major capital costs are identified in Table 2. The operating and maintenance costs for this application are approximately $3.1 billion (1972 dollars).

Table 2. Capital Costs Per Quad for Cotton Residue/Combustion System

Industrial Category	Billions of 1972 $/Quad
Industrial Patterns	7.4
Plumbing & Heating Equipment	7.4
Transportation	1.1
New Construction	2.3
Total Capital Cost	18.2

The major operating residuals for the application are found in Table 3. An environmental effect not noted in the table is the waste heat dissipated into the atmosphere. The amount of heat wasted by the system is many times the useful heat produced and accounts for the relatively high capital cost per Quad.

Table 3. Major Operating Residuals Per Quad for Cotton Residue/Combustion System

Residual Category	Estimated Residuals Per Quad (10^3 tons)
Particulates	9,150
SO_2	850
NO_x	1,750
CO	16,150
Hydrocarbons	1,700
Solid Waste/Ash	104,640

Hydrolysis of Corn Residue

Furfural is an aldehyde with the -CHO group in the α position. Its production was commercialized by Quaker Oats in 1922 (Quaker Oats Co., 1974) and it is obtained from pentosan-containing agricultural residues. Furfural serves primarily as a chemical intermediate for the production of furfuryl alcohol, tetrahydrofurfuryl alcohol, furan, tetrahydrofuran, polytetramethylene ether glycol, or as a precursor of pyrrole, pyrrolidine, pyridine, piperidine, lycine methylfuran, and many other compounds. It is considered in this study as a biomass-derived chemical that can serve as a substitute for a petroleum-derived chemical, thereby potentially sparing oil resources.

The extraction of furfural from agricultural residues involves acid digestion under steam pressure followed by a series of distillations to separate and purify the furfural and other by-products of the hydrolysis (Faith et al., 1957; Paturau, 1969). The material remaining after digestion is then separated into a solid and a liquid fraction by a screw press. The solid residue is granular and composed principally of modified cellulose, lignin and resins (Quaker Oats Co., 1972). The liquid fraction contains the dissolved carbohydrates and spent acid.

The furfural is recovered from the vapor by passing it through a distillation column; the overhead is condensed and a furfural layer and a water layer separated by decanting (Faith et al., 1957). The water layer in the decanter yields highly volatile by-products, namely, methyl alcohol, methyl acetate, and acetic acid. The production of methyl alcohol and methyl acetate equals roughly one-sixteenth of furfural production at the plant while that of acetic acid equals the production of furfural (Lipinsky et al., 1977).

The model system for this study is a large hypothetical facility for furfural production. The processing rate is 135 tons/day of furfural requiring 1588 tons/day corn residue (Lipinsky et al., 1977). Major energy and material inputs into the system are steam (40,000 lb/ton furfural), water (11,000 ft^3/ ton furfural), electricity (250 kwh/ton furfural), and sulfuric acid (50 lb conc./ton residue). The capital costs per Quad of input energy are given in Table 4. The estimated operating and maintenance costs are approximately $21 billion (1972 $) per Quad of end-use energy in the form of furfural.

Table 4. Capital Costs Per Quad for Corn Residue/Furfural System

Industrial Category	1972 $ Per Quad (10^9 $)
Special Industry Machinery	0.71
Fabricated Metal Products	6.15
Fabricated Plate Products	1.92
Plumbing & Heating Equipment	0.44
Structural Metal Products	3.06
Pipes, Valves, & Fittings	3.76
Trucking	1.21
New Construction	13.85
Total Capital Cost	31.10

The major operating residuals are presented in Table 5. It is assumed that the major high energy by-products of the process (e.g., methanol, methyl acetate, and acetic acid) are recovered and sold. This recovery would bolster the overall energy production by the system because these chemicals contain as much energy as the primary product (furfural). The major environmental contaminants are found in the air, water, and land media. A significant temporary land usage is also required to supply the residue.

Table 5. Major Operating Residuals Per Quad for Corn Residue/Furfural System

Residual Category	Estimated Residuals Per Quad (10^3 Tons)
Hydrocarbon	1,012
H_2SO_4 (Vapor)	140
BOD	26,880
H_2SO_4 (Acidity)	2,800
Solid Waste	392,240
Land, Permanent	321 (10^3 acres)
Land, Temporary	140,000 (10^3 acres)

Gasification of Corn and Wheat Residues

The pyrolytic conversion approach - gasification - is examined in this application for the production of a low-Btu gas from corn and wheat residues which can replace natural gas. Gasification is actually a two-stage process. Part of the biomass in the gasifier is combusted with a limited air supply, to provide heat to raise the temperature in the gasifier unit above 1600° F. Under these conditions, the biomass fuel in other parts of the gasifier is pyrolyzed. However, a highly carbonized solid residue, called char, and liquids with high tar contents are also generated. Resultant quantities of these materials depend greatly upon gasifier design and operation.

A commercial unit in operation at Diamond/ Sunsweet, Inc., Stockton, California (Goss, 1978) served as a model for this application. The unit has a capacity of 28.6 tons per day and produces enough energy to sustain a steam production rate of 8500 lb/h (15 psi) at a fuel rate of one ton mulled walnut shells per hour. A natural gas pilot flame is required. A laboratory-scale testing model similar to the unit has been built at the University of California at Davis (Williams and Horsfield, 1977).

In the model system, there are only three unit operations: storage, handling, and gasification. Eighty percent of the input fuel is gasified and the principal by-product is a low-Btu gas (150 Btu/ft^3) with a char residue (20% of input material) as a by-product. The major energy flow into the system is natural gas for start-up or occasionally sustaining the process. Table 6 identifies the major capital expenditures for the gasifier system. These costs apply whether corn or wheat residues are utilized. The operating and maintenance costs for the system is $3.6 billion (1972 $) per Quad end-use energy.

The range of operating residuals which has been estimated for this application is given in Table 7. The temporary land use requirement for corn is significantly less than for wheat because of higher per acre yields. If the char from the process could be used as an energy resource, a significant improvement in overall energy generation by the system would result.

Table 6. Capital Costs Per Quad for Wheat-Corn Residue/Gasification System

Industrial Category	1972 $ Per Quad (10^9 $)
Fabricated Metal Products	0.81
Plumbing and Heating Equipment	0.35
Materials and Handling Equipment	0.02
Transportation	0.09
New Construction	0.25
Total Capital Costs	1.52

Table 7. Major Operating Residuals Per Quad for Wheat-Corn Residue/Gasification System

Residual Category	Residuals Per Quad End-Use Energy (10^3 tons)
Particulates	36-38
SO_2	3- 4
NO_x	52-53.7
Combustible Solid Waste	18,000 - 21,099
Land Use, Permanent	3.3 (10^3 acres)
Land Use/Year	49,000 - 56,000 (10^3 acres)

Fermentation of Sugar Processing Residues

Molasses is obtained as a by-product of sugar processing (both cane and beet sugars). U.S.D.A.'s Agricultural Statistics 1977 estimates that 133,676,000 gallons of molasses were produced from mainland cane and 191,700,000 gallons were produced from domestic beet sugars. Cane molasses is preferred by distillers because of the higher invert sugar concentration, although both types of molasses will support fermentation.

This model process developed for the production of ethanol from molasses is similar to other processes for industrial ethanol production in the United States and overseas (Lowenheim and Moran, 1975; Yang et al., 1977; Paturau, 1969;

Lipinsky et al., 1977; Klostermann et al., 1977; Wilke et al., 1978). The system has a production capacity approaching 200,000 gallons of ethanol per day and uses approximately 3000 tons/day of molasses. This system is scaled after the large Battelle system for sugarcane juice (Lipinsky et al., 1977). The capital costs are summarized in Table 8. The operating and maintenance costs are approximately $13.3 billion per Quad of ethanol energy produced.

Table 9 lists the major operating residuals for the system. Air pollution (from distillation and storage) and water contamination are the major problems. However, it is assumed that by-products of the process (e.g., stillage) are marketable.

Table 8. Capital Costs Per Quad For Sugar Processing Residue/Fermentation System

Industrial Category	1972 \$ Per Quad (10^9 \$)
Plumbing & Heating	0.75
Fabricated Metal Products	1.87
Pumps, Compressors & Blowers	0.002
Engineering & Scientific Equipment	0.01
Special Industry Machinery	0.07
Structural Metal Products	0.10
Metal Plate	0.09
Pipes, Valves & Fittings	1.17
Buildings & Auxiliaries	0.90
Transportation	0.37
New Construction	4.29
Total Capital Costs	9.622

Table 9. Major Operating Residuals Per Quad for Sugar Processing/Fermentation System

Residual Component	Residuals Per Quad End-Use Energy (10^3 tons)
Ethanol (Vapor)	391
Benzene (Vapor)	16
BOD	58
Land Use, Permanent	54.8 (10^3 acres)

LIVESTOCK WASTE APPLICATION

Anaerobic Digestion of Manure

Anaerobic digestion of animal residues has been used in India for many years. Sanghi and Day (1972) report that in 1972 there were about 2,500 anaerobic digesters in rural India producing biogas from cattle dung without destroying the value of the solids as fertilizer. Essentially, only carbon is metabolized into biogas with a heating value of 600 Btu/ft^3. Most nutrients, especially nitrogen, pass through and are discharged in the digested residue.

In the United States, extensive investigations are underway to evaluate process requirements for biogas recovery from beef cattle, dairy cows, swine, poultry, and other animal wastes (Tennessee State University, 1977; Biogas of Colorado, Inc., 1978). One area where anaerobic digestion is close to full-scale production is the Four Corners region of Arizona, Colorado, New Mexico, and Utah, where there are many large beef feedlots.

The process characteristics reported here are based on a model plant designed to process the waste from 25,000 beef cattle. Beef cattle at an average weight of 1,000 lb produce 60 lb of raw manure per head per day, containing 6.9 lbs of total solids, of which 5.9 lbs is volatile solids.

The assumed design of an anaerobic digestion plant for feedlot manure has a process rate of 0.2 lb/day of volatile solids per cubic foot of digester capacity. At 5.9 lb of volatile solids per day per animal, 25,000 head of cattle will produce 147,500 lb of volatile solids, which will require 737,500 ft^3 of digester capacity. This capacity is supplied by three primary digesters 100 ft in diameter by 31 ft high. Three secondary digesters of the same size, with gas-holding covers, are also needed.

The digested sludge (42.5 tons of dry solids per day) is dewatered by 110-hp centrifuges, two on line and one in reserve. The extracted water goes to a controlled algae pond and later is returned to mix with raw manure entering the plant. The algae is harvested and dried as an animal feed supplement; the dewatered, digested residue is used as a fertilizer additive or solar-dried for animal feed.

Assuming a biogas production of 8.5 ft^3/lb of volatile solids, this digestion plant would produce a gross yield of 1.25×10^6 ft^3 of gas per day (Loehr, 1977). The digester gas is purified in an amine absorption step to remove 35% of the CO_2 and all of the ammonia and hydrogen sulfide, resulting in gas with 710 Btu/ft^3.

The capital costs for the process are summarized on a per Quad basis in Table 10.

Table 11 presents the major operating residuals generated on a per Quad basis. The major impact is solid waste from the digesters. This should not be a serious environmental problem if sound land application practices are employed.

Table 10. Capital Costs Per Quad for Manure/Anaerobic Digestion System

Industrial Category	1972 $ Per Quad End-Use Energy (10^9 $)
Cement Cover	2.08
Oil Field Machinery	2.68
Buildings	0.14
Transportation	0.20
New Construction	6.71
Total Capital Costs	11.81

Table 11. Major Operating Residuals Per Quad for Manure/Anaerobic Digestion System

Residual Category	Residuals Per Quad End-Use Energy (10^3 tons)
SO_2	2,570
NO_x	90
Solid Waste	103,700

FOREST INDUSTRY RESIDUE APPLICATION

Cogeneration from Pulp/Paper Residues

The pulp and paper industry is the fourth largest industrial consumer of fuels and electricity in the United States. Paper and allied products industries purchase more than 385 billion kWh equivalent of fuels and electricity per year (Little, Inc., 1976), and consumed (in 1970) 1.5 Quads (Sittig, 1977).

Pulp and/or paper operations are either larger integrated systems (producing both pulp and paper) or smaller nonintegrated systems (producing either pulp or paper). Most of the U.S. paper is manufactured by integrated mills.

The pulping process most prevalent in the United States and selected as the basis of our model forestry residue conversion system is known as the Kraft process. In the Kraft process, under high temperatures (350°F) and pressures (100 psi), the wood chips are cooked for 2-4 hours in an alkaline solution of sodium sulfate and sulfite in order to separate the cellulose fibers from the lignin and other materials (Hall et al., 1977) (Sittig, 1977). The spent cooking liquor, known as black liquor, contains the lignin and the chemicals utilized in the process. The liquor passes through a recovery system, and most of the original chemicals are extended and reused, while the remaining lignin plus other combustible materials are concentrated (55-65% solids). Thereafter, the concentrated liquor is conveyed to the furnaces/boilers and burned to generate heat, steam, and electricity.

It has been estimated that the production of a dry ton of Kraft pulp requires 325 kWh of electric energy as well as 8500 lb of steam at about 80 psi (equivalent to 10.67×10^6 Btu), and that one ton of spent liquor solids burned in the recovery furnace releases 13.2×10^6 Btu (Sittig, 1977).

The model plant studied has one power boiler burning bark and wood residues and two main recovery boilers burning the organic matter of the black liquor. In addition, a turbogenerator unit is employed for electricity generation. This unit is envisioned for a plant which annually processes 200,000 tons pulp and produces 36,000 tons black liquor per year. The major capital costs on a per Quad basis are given in Table 12. The operating and maintenance costs for the system are $0.13 billion per Quad.

Table 12. Capital Costs Per Quad for Pulp-Paper Residue/Cogeneration System

Industrial Category	1972 $ Per Quad End-Use Energy (10^9 $)
Metal Plate	1.41
Engines & Turbines	0.31
Pulp Mills	0.07
Special Industry Machinery	0.20
Transportation	0.15
New Construction	1.43
Total Capital Cost	3.57

Table 13 gives the major operating residuals per Quad. Air and land are the two resources most affected by this technology.

Table 13. Major Operating Residuals Per Quad for Pulp-Paper Residue/Cogeneration System

Residual Category	Residuals Per Quad End-Use Energy (10^3 tons)
Particulates	3,145
SO_x	105
NO_x	699
CO	2,097
Hydrocarbons	2,446
Solid Waste (Ash)	2,897

CONCLUDING REMARKS

The aforementioned biomass technology applications cover the range of conversion options available from combustion to anaerobic digestion. Typically, the capital costs and operating and maintenance costs for thermal conversion (e.g., combustion and gasification) are significantly less than for biological or chemical conversion (e.g., fermentation or hydrolysis).

Depending upon the technology, impacts to air and water can arise from the use of biomass conversion approaches. However, if by-products of some of the approaches are not utilized these impacts could be more significant.

Developing the right technological mix is also an important factor in assessing the large-scale utilization of biomass. No one application will be able to satisfy the future demand. Thus, identification of the appropriate technology mix is necessary.

The micro-scale analyses provide energy information on a per Quad basis, economic data, and residual data in an interrelated fashion. These data are now being processed through the SEAS model to ascertain the consequences of the large scale application of solar technologies.

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