

Whole Tree Energy Power Plant

K. W. Ragland

Dept. of Mechanical Engineering, University of Wisconsin, Madison, WI

L. D. Ostlie

Energy Performance Systems, Inc., Minneapolis, MN

D. A. Berg

R.W. Beck, Inc., St. Paul, MN

ABSTRACT A planned 50 MW Whole Tree Energy (WTE™) biomass-fired power plant and previous pilot-scale and small-scale testing is described. Hybrid poplar trees are planted and grown on land within 80 km of the power plant site. The time from planting to harvest is five growing seasons, and the projected harvest yield is 56 dry t/ha. The harvested trees are trucked to the power plant site and dried in a drying dome, which utilizes waste heat from the power plant. The whole (not chipped) trees are then fed by conveyor into a deep, fixed-bed furnace which provides heat for a high pressure steam boiler-steam turbine-electrical generator. Flyash is removed from the stack gas with a wet electrostatic precipitator, and the ash is pelletized and used as fertilizer for the trees. Nitrogen oxides are controlled with extended over-fire air. A 50 MW power plant requires 18,400 ha of tree farms, which is about 1% of the land within a radius of 80 km. The required land is leased for a 15 year period. The first WTE™ power plant (50 MW) will be built in St Peter, MN, with projected startup in mid-2004. The average present value of electricity from a second 50 MW WTE™ power plant is projected to be \$0.049/kWh, and for 150 MW WTE™ power plant, \$0.036/kWh (year 2000 basis, Federal tax credit for closed loop biomass included).

INTRODUCTION

This article describes a renewable, sustainable, closed-loop system for generating electric power from biomass – the Whole Tree Energy (WTE™) system¹⁻⁶. Farm grown hybrid poplar trees are burned whole (not chipped) in a deep, fixed-bed furnace to generate superheated steam that powers a steam turbine-generator. Exhaust heat is used for air and feedwater heating and fuel drying. The fuel supply, land requirements, power plant technology, equipment testing to date, project economics, and project status are discussed. The first WTE™ system is a 50 MW power plant near St Peter, MN, with startup scheduled for mid-2004.

FUEL SUPPLY

The fuel supply is hybrid poplar and cottonwood trees grown as short rotation woody farm crops. The land is leased from the landowner. Each year for five years 4,000 ha is planted. Over the last 15 years various clones of hybrid poplars have been bred to be fast growing and disease resistant. Improvements in the genetic stock are ongoing. Hybrid poplars are beginning to be widely used in the forest and paper industries. Cottonwood, which is in the same genus, is also very fast growing and disease resistant. Poplars will grow almost anywhere but best yield for energy crops is obtained by following proper agricultural practice. The trees grow tall and straight with relatively small branches. In the several years of operation before the energy crop is established, waste wood, over-aged stands, and natural gas will be used as the fuel.

PLANTING AND FARMING

Cuttings from two-year-old stool bed trees are used to establish the tree farms. The two-year-old trees are harvested in winter and cut into 25 cm lengths with diameters of 8 mm to 25 mm. The cuttings are stored in boxes in an industrial freezer. The dormant cuttings are planted in May when the soil temperature reaches 10°C. A rapid planting machine inserts a cutting into the soil such that one bud is exposed to the air. The cuttings are planted on 1.7 m centers, and a total of up to 4400 cuttings per hectare are required.

The most successful clone developed to date for the upper Midwest is hybrid poplar NM-6 (Nigra X Maximawitzii), and this will be the main cutting. Other fast growing and disease resistant clones such as the eastern cottonwood varieties will also be used. Cuttings will be purchased from nurseries in Wisconsin, Minnesota, Michigan, North Dakota and Oregon.

A pre-emergent herbicide is applied after planting, which provides weed control for most of the season. Young hybrid poplars cannot out-compete weeds. One tilling may be required in the first year for weed control, but not in the following years. A single final application of pre-emergent herbicide is applied in the second year. The clones selected have good pest resistance but some pest management may be required. Nitrogen, phosphorous and potassium levels in the soil must be maintained for optimum growth. The inorganic requirements are only about 10% of that required for a corn crop.

The main source of nitrogen is from decomposition of fallen leaves. Flyash pellets from the biomass-fired power plant are applied to the fields once during the five year growing cycle to recycle the phosphorous, potassium and other trace elements.

HARVESTING AND TRANSPORTING

The trees are ready for harvest beginning in the fall of the fifth growing season. The trees are typically 15-20 cm diameter and 12-14 m tall. A special harvesting machine is being designed by EPS with a grant from the U.S. Department of Energy. This machine, which is mounted on four rubber tracks, grabs the tree, cuts it off at the base, and holds the tree upright in an accumulator, while continuing to move down the row at up to 9 km/h. Near the end of the row the trees are loaded into a trailer carrying a 25 ton load of whole trees. In applications where wider row spacing and longer harvest cycles are used, trucks may be directly loaded when a single row produces more than 25 tons. A 50 MW plant requires 52 truck loads per day of whole trees.

After harvesting, the poplar trees sprout from the stumps and grow vigorously with little attention except fertilization with ash pellets from the power plant. Harvesting is done every fifth year.

PROJECT SITE AND LAND REQUIREMENTS

A 30 ha site for the power plant is needed which has good road access, is close to an electric transmission line, has a natural gas supply for startup, and a makeup water supply. Approximately 6 ha are needed for the drying dome and power plant, while the remaining 24 ha is to be planted with trees to provide a noise barrier and be aesthetically pleasing. Water loss is due to cooling tower evaporation and boiler water blowdown.

The dedicated farmland should be within 80 km of the power plant site. The best soils for poplar trees are loams, sandy loams, and clay loams. Relatively fertile soil is recommended. Planting in very sandy soil is not recommended unless a sufficiently high water table is present. Areas prone to summer flooding should be avoided but poplars can tolerate standing water for short periods of time. Soils should be void of a hardpan layer. The soil pH should be in the range 5.5-7.5, but up to 8.4 can be tolerated by some cottonwood clones. The slope should be less than 14 degrees (or 25%) for efficient harvesting because of mechanical constraints. Five growing seasons are required to harvest. The yield is a function of the soil quality, tree spacing, clone type, fertilization, cultivation, pesticide application, and most importantly water availability. The design yield is 56 dry tons per hectare after five growing seasons. For a 50 MW power plant 20,000 ha are required, which is 1% of the land within an 80 km radius. If each tree farm

averaged 32 ha then a total of 625 fields would be needed and 125 fields would be planted each year.

POWER PLANT TECHNOLOGY

The key power plant technologies are the drying and storage dome, the furnace, the boiler, steam turbine, generator, and emissions control equipment. The general layout of the plant is shown in Fig. I.

DRYING AND STORAGE DOME

Whole trees are delivered to the drying and storage dome (Fig. I) at the rate of 52 trucks per day, and the trees are removed from the trailer truck by a tower crane with grapple. A 30 day supply of wood totaling 19,000 oven dry tons is maintained in various stages of drying. The pile is 24 m high by 85 m diameter (this is based on a pile density of 272 kg/m³ at 44% moisture). The dome, which is a pressurized two-layer fabric facility similar to those used to cover sports stadiums, is 36 m high by 150 m diameter. Heated air from heat exchangers, which transfer heat from the furnace flue gas to the drying air, is circulated by means of zoned ducting underneath the pile and flows up through the pile and out through an opening in the top of the dome. The drying air enters the drying dome at 55°C and exits at 23°C. The delivered wood typically has 44-50% as-received moisture, and after 30 days it is dried to 20-25% moisture. The whole trees are removed from the stack in the dome on a first-in, first-out basis by the overhead crane with a specially designed grapple and placed on a conveyor in batches for delivery to the furnace/boiler.

There is a possibility to plan for greenhouse space between the outside of the tree drying pile and the dome walls, pending consideration of safety issues. The greenhouse area available in the drying dome is up to 9300 m².

FURNACE

Whole tree batches are transported on the conveyor to the furnace charge chamber (Fig. II). While on the conveyor a heavy duty sectioning saw cuts the batch to length and the batch (up to 4.5 ton) is pushed into the charge chamber from the top. The top door closes, sealing the chamber and a charge ram forces the wood through a furnace entry door and onto the top of the fuel bed. The fuel bed, which is typically 3 - 4 m deep, is supported by a patented water cooled grate with controlled circulation. Preheated air from a second heat exchanger, which transfers heat from the flue gas to the furnace air, flows upward under the grate and also above the fixed fuel bed (over-fire air). The furnace design heat release rate of 7.8 MW/m² based on pilot scale test results (see below). For a

50 MW (electrical) power plant the required grate size is approximately 6 m long by 3 m wide.

The combustion process involves a patented three-stage process:

- (1) Char in the bottom 30-60 cm of the deep bed burns on the grate where available oxygen is consumed. The hot gases from the burning char flow upward through the fixed bed of whole trees and drive the volatiles from the wood (pyrolysis). As the char at the bottom is consumed, the bed partially subsides and another batch of wood is fed from the charge chamber above the bed.
- (2) Above bed over-fire air is strategically mixed with the volatiles, which consist primarily of CO, CO₂, H₂, CH₄, H₂O, N₂ and tars. Combustion of the volatiles proceeds, the tars are burned out, and heat is transferred to the boiler walls and convective tubes. Reactions above the bed occur first in a reducing environment, and then excess air is added gradually to the upper combustion zone.
- (3) Any char that falls through the openings of the grate at the bottom of the bed is collected on a lower grate and burns out below the bed.

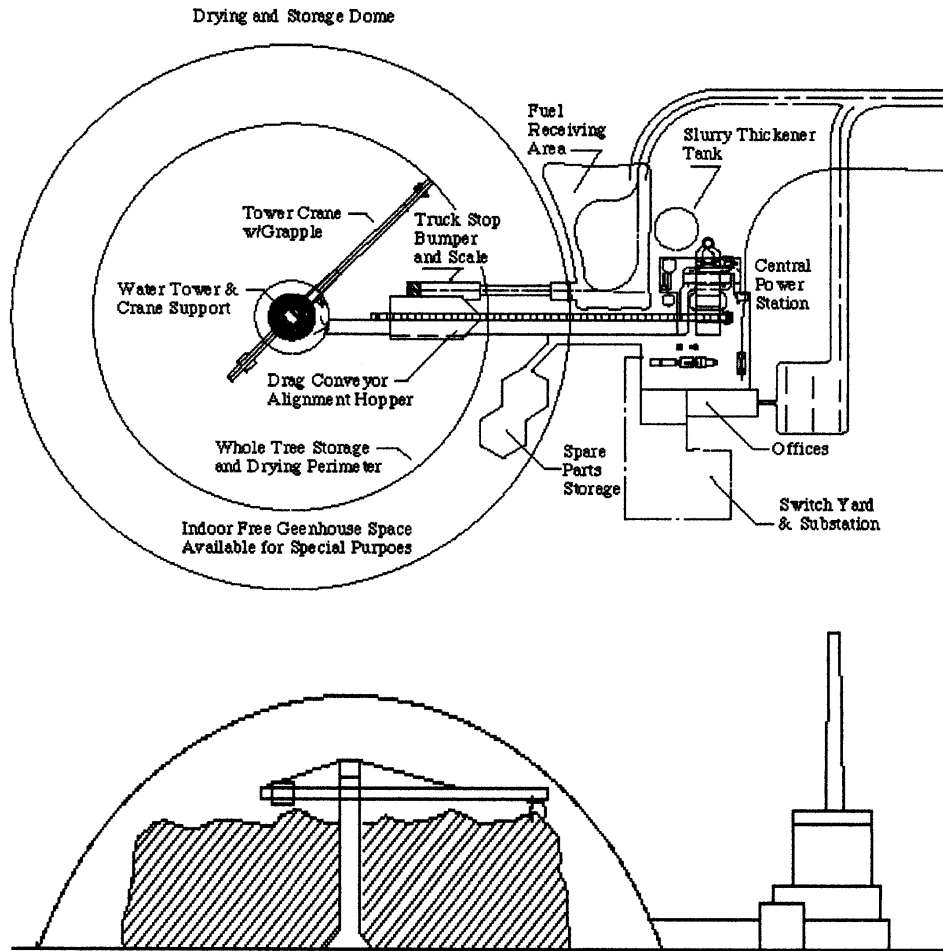


Fig. 1 Top and side views of drying/storage dome and power plant.

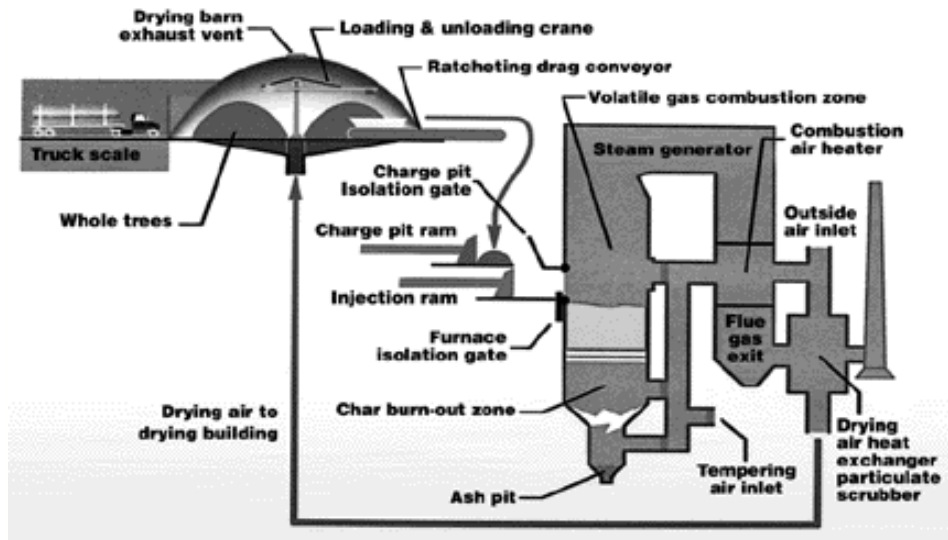


Figure II. Schematic showing furnace, ram feeder, steam generator, flue gas heat exchanger, and drying dome.

BOILER-STEAM TURBINE-GENERATOR

The boiler produces 150,000 kg/h of steam at 13.8 MPa and 540°C exhausted to a pressure of 6 kPa absolute. The steam turbine is a dual casing, single axis machine with six extraction points and one reheat at 540°C. The turbine efficiency is 43.8%. The generator is rated at 57,800 kVA, 3600 rpm, 3-phase, 60 Hz, 13.8 kV. The generator has a gross capacity of 52.4 MW to provide for 4.8% auxiliary power for boiler feedwater, scrubber and cooling tower pumps; combustion air and wood drying air fans; crane, conveyor, and ram feeder power; and miscellaneous power. The expected boiler efficiency is 83%. The overall efficiency of the power plant⁶ is expected to be 33% (based on the higher heating value) for the first plant.

EMISSIONS CONSIDERATIONS

Particulate control is by means of either a wet scrubber or a wet electrostatic precipitator located after the condensing heat exchanger. The choice of particulate control equipment depends on the degree of control required. The particulate slurry collected by the scrubber or precipitator is circulated through a pug mill that de-waters and pelletizes the ash. The ash pellets are spread on the tree fields as a fertilizer. The ash content of the wood is less than 1% so that a maximum of 5 t/day are collected and pelletized. The

particulate emission standard to be met for new wood fired power plants in the State of Wisconsin, for example, is based on best available control technology (BACT) and can be expected to be about 21 g/ 10⁶ kJ.

Nitrogen oxide control is by means of over-fire air jets which are located at strategic positions above the reducing zone of the fuel bed. It is expected that nitrogen oxide formation from fuel nitrogen will be small because is of the extended reducing zone of the fuel bed. The nitrogen oxide emission standard for wood fired power plants is often based on BACT and is set on a case by case evaluation. Sulfur dioxide and carbon monoxide emissions are very low and emission standards do not apply. However, CO is used as a surrogate for products of incomplete combustion (PICs), and it is likely that the CO emissions would be limited to 300 ppm (dry volume basis) at 7% oxygen.

TECHNOLOGY TESTING TO DATE

Planting Tests: A prototype machine has been developed to plant 25 cm long tree cuttings at a rapid rate. Approximately 180,000 cuttings were planted at the rate of 1 per second in a single row. In the operational version of the planter six rows at a time will be planted. The planter can be used on unprepared Conservation Reserve Program land and difficult-to-farm land also.

Harvesting, Loading, and Transportation Tests: Tree harvesting at the rate of 45 green t/h has been demonstrated using a single harvesting “train” of one feller-buncher, one skidder, and one loader. Transportation of 27 ton whole tree loads on logging roads and public highways was done. Crowns and limbs did not pose a problem with loading or transporting whole trees.

Stacking Tests²: Whole hardwood trees were stacked to a height in excess of 30 m. Each layer of trees was placed at 90° to the layer below in a 21 m by 21 m wide array. The weight of the trees tend to compress a notch in the wood where other trees made contact, which enhances the stability of the stack. As a test, a 90 kN side load, which was applied to trees near the top of the stack, had no visible affect on the tree stack. In another test a stack with a 110° angle of repose overhang was created without any apparent instability. Thus the lateral stability of a large stack of whole trees (tops and limbs intact) is exceptional.

Drying Tests²: A 21 m by 21 m by 26 m tall stack of whole hardwood trees was supported by an air distribution manifold. Air was heated by a heat exchanger using a propane burner and ducted into the distribution manifold. The stack of trees was dried with 58°C air for 30 days, and the average moisture level was reduced from 44% to 20%. There was no pressure drop through the stack of trees because of buoyancy; rather the pressure

was -125 Pa at the base of the stack. These tests established the feasibility of drying a large stack of green trees with waste heat from the flue gases.

Combustion tests² were conducted at the Bay Front Unit No. 3 of Northern States Power Co. in Ashland, WI. The coal-fired underfeed stoker with boiler rated at 45,400 kg/h steam at 5.1 MPa drum pressure and 455°C was modified to receive 4.6 m long whole tree sections from a charge chamber by means of a ram feeder. A higher pressure over-fire air system was added. The tests successfully demonstrated the feasibility of replacing coal with logs on a grate without a loss in boiler performance.

Pilot-scale combustion tests^{2,8} of a deep fixed bed of sectioned hardwood trees on a grate were conducted in a 1.4 m by 2.6 m by 6 m high test furnace located in Northern Minnesota (Fig. III). Under-fire air was preheated to 275°C using a two-pass plate and frame heat exchanger. The air flow rate was set at 565 kg/min which gave an air velocity under the bed of 4.0 m/s. The fuel bed, which was supported by an air cooled grate, was maintained at a depth of 3.7 m by feeding wood into the top of the furnace with an inclined chain conveyor. The tree sections were 2.5 m long, with log diameters up to 20 cm, and the average moisture level was 31.6%. The weight of each tree section was measured on a weighing table before being placed on the conveyor. The average void fraction of the bed was 0.65. There was no overfire air and combustion/pyrolysis products were vented to the atmosphere. Based on the wood feed rate required to maintain the level of the bed over a 2 hr period, the average effective heat release rate during the tests was 10 MW/m². These tests demonstrated the intense nature of the combustion and pyrolysis in a deep bed of sectioned whole trees. From the measured wood consumption rate and data from single log tests (see below) a computer model of a deep fixed bed was developed and validated⁸. The model relates heat release rate to under-grate air flow and preheat, fuel moisture, size and void fraction, and bed height. Based on this, a design heat release rate of 7.8 MW was selected for the first full-scale unit.

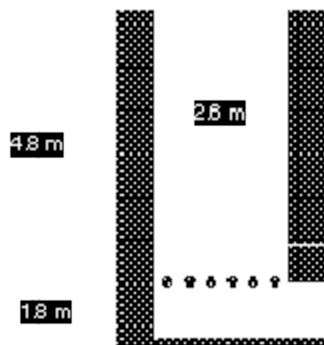


Figure III (a) Pilot-scale, open-top furnace test rig;

Figure III (b). Heat exchanger for preheated combustion air.

*Single log combustion tests*⁹ were conducted at the U. S. Forest Products Laboratory in Madison, WI, in a specially designed furnace that was supported by load cells (Fig. IV). These single log tests established the burning rate of individual logs up to 20 cm in diameter in high temperature oxidizing and reducing environments and confirmed the high heat release rate observed in the pilot scale tests. The detailed data obtained was used to develop a computer model⁸ that simulates the performance of the deep fixed-bed furnace over a range of conditions.

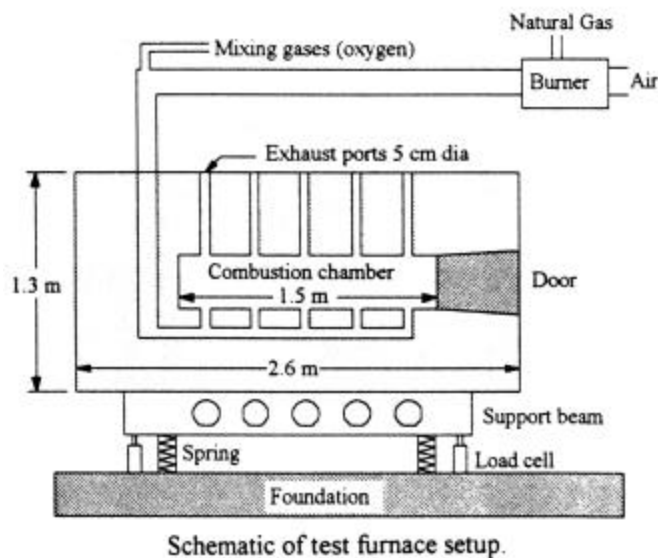


Figure IV. Furnace to obtain burning rate of single logs.

Scrubber Tests: The wet scrubber was tested in 1978 at the Sherburne County Generating Station of Northern States Power on Unit 1, a 757 MW coal-fired unit. In this unit the combustion products were ducted to 11 scrubbers each cleaning the equivalent of 68 MW of gas. The “multiple angle scrubber” was installed in one of the scrubbers replacing the existing rod scrubber. Particulate emissions averaged $174 \text{ g}/10^6 \text{ kJ}$ on coal based on follow-up tests. L. D. Ostlie was granted US patent number 4,313,742 in 1982 for the multiple angle scrubber. If the wet scrubber is deemed to be inadequate, a wet electrostatic precipitator will be used.

ENVIRONMENTAL IMPACT

Energy crops provide vegetative cover throughout the year, reducing soil erosion and improving wildlife cover, unlike annual row crops. Much lowered applications of agricultural chemicals and reduced tillage benefit water quality. Conversion of agricultural land from row crops to woody crops improves soil structure, organic matter content, and water quality. Woody crops develop an extensive root structure that adds organic matter to the soil, slows wind and water erosion, and helps to reduce soil compaction. Soil nitrogen and inorganic nutrients are maintained by means of a controlled combination of fertilizer, leaf litter, and fly ash pellets from the power plant. In regions with high levels of nitrate pollution in the ground water, planting hybrid poplar

trees has been shown to reduce the nitrate levels by a factor of ten or more when the water table is 1.5 m or less below the surface¹⁰.

Woody crop cover in agricultural areas benefits a wide variety of birds, small mammals, and deer. Woody crops provide edge effects and corridors with native habitats thereby improving wildlife diversity. Plots averaging about 32 hectares are envisioned so that landscape diversity is preserved.

The Whole Tree Energy power plant is clean burning, and should meet all Federal and State emission standards. The power plant is carbon dioxide neutral since the carbon emitted by the power plant is balanced by the carbon previously sequestered by the trees and roots.

PROJECT ECONOMICS

Project costs consist of fuel costs, capital equipment and construction costs, fees, operations and maintenance, and financing costs. Farmland rent for trees is assumed to be \$173/ha/year. The estimated cost to establish and tend the trees is \$760/ha for the first year and \$543/ha for the second year; each year thereafter is \$247/ha. Harvesting and transporting the trees to the power plant site at the end of the fifth growing season is \$402/ha. For a new power plant one-fifth of the acreage is planted in each of the first five years; then the trees are cut in five-year periods. The cost of the fuel, excluding establishment, but including rent, tending, harvesting and transportation is \$1.35/10⁹J based on year 2000 costs.

The amount of land required depends on the tree yield, power plant efficiency, and the capacity factor. The average biomass yield was assumed to be 11.3 dry ton/hectare. The power plant efficiency is based on a dry higher heating value of 20,200 kJ/kg. A power plant annual capacity factor of 86.3% was assumed. Power plant sizes of 25, 50, and 150 MW were considered.

Table 1. Fuel supply for 20 year period.

Net Power Plant Size* MW	Power Plant Efficiency %	Wood Growth Rate Dry ton /ha/yr	Total Land hectare
25	28.4	11.3	10,520
50	32.5	11.3	18,400
150	34.1	11.3	52,610

Capital equipment includes fuel handling, storage, drying and feeding systems; steam generator and support systems; turbine-generator and support systems; condensate and feedwater systems; circulating water and treatment systems; electrical and control systems; power plant facility; and power station construction. Engineering, procurement and construction costs on a turnkey basis are shown in Table 2 along with additional site costs, fees and contingencies.

Table 2. Capital costs (year 2000 basis).

Power Plant Size (MW)	EPC Equipment Unit Costs (\$/kW)	EPC Equipment Costs (\$ million)	Site Costs, Fees, Contingen. (\$ million)	Tree Farm Establish. (\$ million)	Total Capital Cost (\$ million)
25	1840	46	18	21	85
50	1500	75	26	37	138
150	1090	163	52	106	321

To fund the project the assumed financial arrangement is 25% equity and 75% debt. Return on equity is assumed to be 25%, and interest on the debt is assumed to be 8.5%. Hence, the effective interest rate is 12.63%. The annual operating costs are \$3.2 million, \$3.9 million, and \$8.6 million year respectively for the three power plant sizes on a year 2000 basis, excluding the fuel. The property tax rate is 2.1% in Wisconsin. For power plants that are over 50 MW and sell at least 95% to a power company that sells at retail, a gross receipts tax can be paid instead of a property tax, which is 3.19% of the sales revenues and is a significant savings over a property tax. No tax moratorium was assumed. No federal capital contribution was assumed, but a closed loop biomass tax credit of 1.79 cents/kWh was taken for the year 2000 and escalated at 2.6% per year for 20 years. Year 2000 costs were calculated by discounting the revenues each year using 3.75% discount rate, which was the rate used to escalate operating costs. The 20 year cumulative discounted revenues were divided by the 20 year cumulative value of electricity delivered. The projected 20 year average present value of electricity for the second WTETM power plant is shown in Table 3.

Table 3. Average present value of electricity (year 2000 basis).

Net Power Plant Size (MW)	Cost of Electricity* (\$/kWh)
25	0.064
50	0.049
150	0.036

*includes Federal tax credit for closed loop biomass

CURRENT STATUS OF WHOLE TREE ENERGY

Research on poplar tree clones for bioenergy by Oak Ridge National Laboratory and its affiliated Universities, by the US Forest Service-North Central Forest Experiment Station, and by members of U.S. Poplar Council is extensive. As a result of this research, an EPS affiliated nursery is currently growing 8 ha of NM-6 hybrid poplar stool trees. Other commercial nurseries are also growing hybrid poplar and willow clones for cuttings.

EPS holds patents in 30 countries in North and South America, Western and Eastern Europe, Asia, and Australia covering the Whole Tree Energy technology. A rapid harvesting machine has been designed and is being built and tested under a contract with the U.S. Department of Energy. A machine for harvesting whips (two-year-old trees from which the 25 cm long cuttings are made) is being developed. A prototype machine for rapid planting of the tree cuttings also is being developed.

The first Whole Tree Energy power plant is under development by EPS/Beck Power, which is a limited liability corporation formed by Energy Performance Systems, Inc. (EPS) and R. W. Beck, Inc. EPS develops and holds patents on the WTE™ bioenergy technology, and R. W. Beck is an engineering consulting company. In January 2000 a power purchase agreement between Northern States Power and ESP/Beck Power for a 25 MW Whole Tree Energy™ power plant was approved by the Minnesota Public Utilities Commission. In late April NSP expanded the project to 50 MW. Startup is scheduled for the mid-2004 at a site near St. Peter, MN. The agreement covers 20 years of operation at a capacity factor of 86.3%. Private equity and debt arrangements are being negotiated. Individual long-term (15 yr) leases of land for tree farms are being sought with landowners within 80 km of the power plant site.

ACKNOWLEDGEMENT The information collected for this article was made possible in part by a grant from the Wisconsin Energy Bureau.

REFERENCES

1. EPRI (1993) *Whole Tree Energy™ Design, Volume 1: Engineering Evaluation*, TR-101564v.1, Electric Power Research Institute.
2. EPRI (1993) *Whole Tree Energy™ Design, Volume 2: Program to Test Key Elements of WTE*, TR-101564v.2, Electric Power Research Institute.

3. EPRI (1993) *Whole Tree Energy™ Design, Volume 3: 100 MW Design*, TR-101564v.3, Electric Power Research Institute.
4. EPRI (1995) *100 MW Whole Tree Energy™ Power Plant Feasibility Study, TR 104819*, Electric Power Research Institute.
5. Lamarre, L. (1994 Jan-Feb) Electricity From Whole Trees, *EPRI Journal*, 16-24.
6. Ostlie, L. D. & Ragland, K. W., (1998) High Efficiency Bioenergy Steam Power Plant, in *Bioenergy '98*, pp. 772-781.
7. Withrow, K., Wichert, D. & Moran, D. (1999) The State of Wisconsin Energy Geographic Information System, Wisconsin Energy Bureau, Department of Administration.
8. Bryden, K. M. & Ragland, K. W. (1966) Numerical Modeling of a Deep, Fixed Bed Combustor, *Energy and Fuels*, American Chemical Society, 10, 269-275.
9. K. M. Bryden & K. W. Ragland (1997) Combustion of a Single Log under Furnace Conditions, *Developments in Thermochemical Biomass Conversion*, (Ed by A.V. Bridgewater & D. B. G. Boocock), pp.1331-1345, Blackie Academic and Professional.
10. Licht, L. A., Schnoor, J. L., Nair, D. R. & Madison, M. F. (1992) Ecolotree Buffers for Controlling Non-point Sediment and Nitrate, ASAE paper 922626, Nashville, TN.