assumed, with no inter-district transport.) If the conventional technology coal-fired power plant is used for comparison, only in one district (Mangalore) and only for SO_2 would the increased use of existing captive generation be a worse option than the centralised option. If the advanced technology coal-fired power plant is used for comparison, then lower SO_2, NO_x or particulate emissions can be expected in 9 out of 17 districts considered. Increases in SO_2 emissions due to increased capacity utilisation of diesel captive plants in the Mangalore division is a matter of particular concern because the division is located upwind of a region with relatively high acid rain potential.

- Increased statewide diesel particulate emissions due to increased captive used would, however, be about 27% of existing diesel particulate emissions due to transport operations. This presents a serious increase in fine particulate emissions that could have longer atmospheric lifetimes and therefore be likely to disperse across districts.
- A final option considered was to retrofit emission controls for captive power plants at an additional cost of Rs 9000/kW to reduce emissions by 80%. This option was found to be up to 30% more cost-effective statewide for SO_2 reduction and between about 10-96% cheaper for NO_x and particulate reductions in individual districts compared with either of the centralised options.
- Local resource constraints (water, land), other pollution effects (groundwater, surface runoff), and biodiversity concerns that arise due to fuel-handling and evacuation of power were not considered in this analysis. In addition, concentration and exposure modelling was not carried out even for air emissions. ■

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Note

1. A division is an administrative unit of a state that groups together several districts. Mangalore division contains Dakshina Kannaada, Uttara Kannada and Kodagu districts.

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Small-scale biomass fuel cell/gas turbine power systems for rural areas

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1. Introduction

The use of small-scale diesel generators fired with gasified biomass and pilot oil for rural applications is growing [Kumar, 1997; Singh, 1996; Turnbull et al., 1996]. These systems are simple and low in cost, but because they have low thermodynamic efficiency (~25%[1] at a scale of ~100 kW), their use is limited to low-cost biomass feedstocks such as agricultural residues and gathered fuelwood. Dedicated biomass energy crops could potentially be a much larger resource, but their higher cost means that they can be economically viable only if a technology is developed that is significantly more energy-efficient than existing technologies, yet still sufficiently low in cost. This paper presents an analysis of a technology that has good prospects for satisfying these criteria – a power system consisting of a biomass gasifier coupled to a fuel cell and a micro-turbine bottoming cycle.

In this system the gasifier is commercial technology, the micro-turbine is nearing commercial readiness, and the fuel cell is still under development but expected to be commercially available at the scale needed for the present application in less than five years [Penner et al., 1995]. The micro-turbine and the fuel cell are high-tech pieces of equipment used to date mainly in aerospace and military applications, so they may appear to be poorly suited to rural power generation. However, recent cost-cutting and performance-enhancing advances have made them highly attractive for commercial applications in transportation and distributed generation, where low cost and simple design are important.

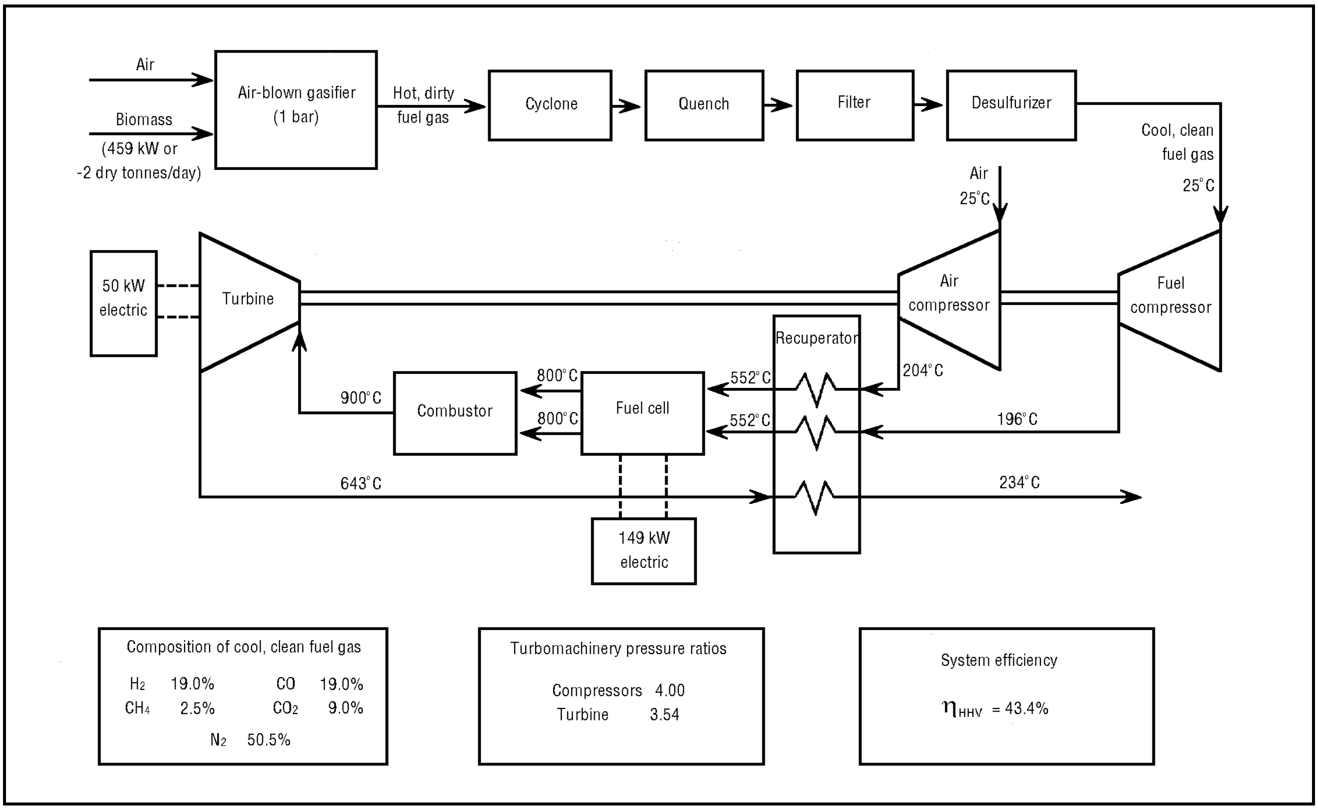

Figure 1. Solid oxide fuel cell/gas turbine power plant powered by biomass gasified in an air-blown gasifier.

2. System design

This analysis considers an electric power-generating technology consisting of a fuel cell/gas turbine combined-cycle power generator in a configuration that is currently attracting great interest because it offers prospectively low capital cost, near-zero local air pollutant emissions, high reliability, low operation and maintenance requirements, and high thermodynamic efficiency – 60-70% is expected on natural gas [Bakker et al., 1996; Harvey and Richter, 1994a,b; METC, 1996, 1997; Veyo and Lundberg, 1996]. For the biomass application considered here a simple, rugged, 200 kW design is proposed that offers the promise of low cost and an efficiency sufficiently high (>40%) for the system to have attractive economics. A system of this size could be supported by the biomass grown on less than 40 hectares, assuming an average yield of 15 dry tonnes/ha/year.

As shown in Figure 1, the biomass is gasified and the fuel gas is cooled and cleaned. Then the fuel gas and air are compressed and preheated in the gas turbine recuperator using heat recovered from the turbine exhaust. The fuel and air are then fed to the fuel cell, which consumes ~85% of the energy in the fuel stream and ~20% of the oxygen in the air stream and releases waste heat in the electrode exhaust streams. The remaining fuel in the fuel cell exhaust is combusted and the combustion products are expanded through the turbine. The turbine exhaust is cooled in the recuperator and, if necessary, the warm stack gases could be used for biomass feedstock drying. The full-load performance of this system was modelled and optimized using commercially available ASPEN+ process simulation software, which calculates mass, heat, and mechanical work flows in simulated chemical processes using tabulated thermodynamic data. All components that affect the mass, heat, and work balances have been included in the simulated models on the basis of projected performance characteristics. (See Table 1.)

2.1. Gasifier and gas cleanup

The gasifier chosen for this system is an atmospheric pressure, air-blown, directly heated, downdraft gasifier that has undergone extensive testing in the laboratory and field [Mukunda et al., 1993, 1994a,b] and is now being commercialized at scales from 3.7 kW to 500 kW. The gasifier is simple in design in that it requires no pressurization or lockhopper feeding, no oxygen plant, no steam generation, no fluidization, no circulating heat exchange medium or in-bed heat exchanger tubes, its start-up procedure is trivial and quick, and it requires neither hot gas clean-up (with ceramic candle filters, for example) nor heat exchangers for syngas cooling (since the gasifier is not thermally coupled to the downstream power plant). The clean-up system is therefore simple, consisting of a small cyclone integrated with the gasifier outlet, a cold-water quench, and a sand-bed filter. The unique design of this gasifier establishes thermodynamic and oxidative conditions that severely limit the generation of tar, the excessive production of which would otherwise necessitate measures such as cracking the tar in a separate reactor or scrubbing out the tar and thereby sacrificing a portion of the energy content of the gas. At full load, tar levels from a 100 kW gasifier are measured to be ~10 mg/m^3 after clean-up [Mukunda et al., 1994a]. Particulates and alkalis (which tend to condense on the particulates at low temperatures) are assumed here to be adequately removed

Table 1. Baseline system parameters and results

Net fuel cell power	149 kW	Net gas turbine power	50 kW
Power conditioning, DC-AC	97%	Generator efficiency	94%
Fuel cell voltage	0.7V	Compressor pressure ratio	4
Oxygen utilization	21%	Turbine inlet temp	900ºC
Hydrogen utilization	85%	Compressor efficiency	80%
T_{inlet}, for fuel cell	552ºC	Expander efficiency	84%
T_{outlet} for fuel cell	800ºC	Recuperator exhaust temp	234º C
Fuel cell pressure drop, Δ p/p	3%	Recuperator pressure drop, Δp/p	3%
Gasifier cold gas efficiency	79%	Recuperator effectiveness	85%

by the cyclone, quench, and filter. Whether or not sulfur removal is needed is uncertain at this time; it depends on both the sulfur tolerance of the fuel cell and the sulfur content of the biomass. If sulfur removal is necessary, a relatively simple removal technology such as a zinc oxide guard bed is likely to be adequate since most biomass feedstocks will have very low sulfur content.

The cold gas efficiency of this gasifier has been measured at 77.3-80.3% (depending on load) using wood chips with a moisture content of 10-12% [Mukunda et al., 1994a]. For our modelling we have assumed a cold gas efficiency of 79%. The gasifier has been demonstrated to operate reliably on wood chips with a moisture content as high as 25% [Mukunda et al., 1993], but optimal performance might require drying to less than half this moisture level. Field drying of a freshly cut tree (~50% moisture) via transpiration through its leaves can sometimes lead to rapid drying to moisture levels in the low 20% range. Also, cooling stack gases in a biomass dryer from 234ºC to 100ºC could potentially drop the moisture level of fresh biomass to 10%. Further study is needed to ascertain the magnitude of a possible efficiency penalty due to flue-gas drying.

2.2. Fuel cell

Fuel cells are "electrochemical engines" that efficiently convert fuel into electrical power without combustion and without the pollutants that generally accompany combustion [Kartha and Grimes, 1994]. Fuel cells function similarly to batteries in that an electrochemical reaction converts chemical energy directly into electricity, but in the case of fuel cells the chemical energy is supplied continuously from an external fuel source.

This study focuses on high-temperature fuel cells, with which a gas turbine bottoming cycle is attractive as an efficient use of the fuel cell waste heat and the unutilized fuel in the fuel cell exhaust. For this small-scale rural application, the solid oxide fuel cell (SOFC) seems to be more promising than the molten carbonate (MCFC) alternative because (1) the operating temperature of the SOFC (~900-1000ºC) is higher than that of the MCFC (~600-700ºC) and is compatible with a gas turbine bottoming cycle, obviating the need for a much more costly and complex steam-Rankine cycle, (2) the SOFC is likely to be better suited than the MCFC to operation at the pressure required for coupling to a gas turbine, although its higher operating temperature will make the materials requirements more stringent, (3) the SOFC is a solid-state device while the MCFC requires management of a liquid electrolyte that poses corrosion problems and is less tolerant of thermal cycling, (4) the MCFC system is more complex because CO_2 must be recycled from the anode exhaust to the cathode, where it is consumed as a reactant, and (5) the lifetime and cost of the SOFC are likely to be superior in the long term. Promising power cycles based on MCFCs and steam turbines have also been considered [Lobachyov and Richter, 1997], and they could demonstrate efficiencies as high as 53% (higher heating value basis), but the complexity of these configurations makes them practical only at much larger scales (at least several tens of MW) than that considered here.

SOFC demonstrations fueled by natural gas ranging in size up to 25 kW have been successfully undertaken over the past several years. If successful, the operation of a 100 kW cogeneration system currently being installed at a district heating plant in the Netherlands [METC, 1997] will demonstrate that there are no prohibitive problems associated with scaling up SOFC technology to the scale required for the system considered in this study. Westinghouse has constructed and commissioned a pilot manufacturing facility capable of producing 4MW/yr of SOFCs and has announced plans to accept commercial orders for SOFC/GT systems by the year 2000 [METC, 1996].

2.3. Gas turbine and recuperator

A micro-turbine with a recuperator (i.e., a heat exchanger that raises efficiency by preheating reactants with heat recovered from turbine exhaust) serves as a simple means of generating additional power and increasing efficiency using the high quality waste heat from the fuel cell and residual fuel in the fuel cell exhaust. Recuperated microturbines are now being developed for small-scale distributed generation and automobiles [Wadman, 1995]. Their expected high reliability and low cost derives from several technical features: using air bearings instead of lubricated bearings, which minimizes the need for moving parts by having a single compressor/turbine/generator shaft with no gear-box; having a relatively low turbine inlet temperature to eliminate the need for turbine blade cooling and the use of expensive materials (in the recuperator and other components); and operating at a low pressure ratio, which permits a single-stage compressor. Such a turbine design, especially for small-scale applications, is far preferable to a heat recovery steam generator and steam tur-

Table 2. Estimated cost of electricity from a 200 kW_e biomass-fueled solid oxide fuel cell / gas turbine power plant

	Unit cost[1] per kW ($)	(Lifetime)	Net present value incl. replacements ($)
Solid oxide fuel cell stack[2]	¾ × 500	(7.5 years)	692
Power conditioning (DC to grid)[3]	¾ × 120	(30 years)	90
Gas turbine and recuperator[4]	¼ × 300	(15 years)	93
Gasifier[5]	35	(3.75 years)	110
Gas clean-up[5]	50	(10 years)	77
Capital subtotal	625		1,062
Balance of plant[6]	156		156
Indirect costs[7]	156		156
Installed capital			1,374
Capital costs/kWh[8]			0.023
Labor costs/kWh[9]			0.006
Fuel costs/kWh[10]			0.012
Maintenance & overhead costs/kWh[11]			0.010
Total cost/kWh			0.051

Notes

1. The fuel cell provides ¾ of the net power and the gas turbine 1/4, so costs are weighted accordingly.
2. Estimate adapted from EPRI [1996] by subtracting b.o.p. and indirect costs.
3. Personal communication, R. Wills, Advanced Energy Systems, Wilton, NH, April 4, 1997.
4. Personal communication, R. Mackay, Capstone Turbine Corp, Tarzana, CA, April 30, 1997.
5. Consistent with Sridhar [1997] and Satyanarayana [1999].
6. Balance of plant costs are taken as 25% of other capital costs as per Wyman et al. [1993].
7. Indirect costs that are 20% of capital are assumed to be appropriate for factory-manufactured, relatively simple, quickly constructed power plants [Sabisky, 1996].
8. Assumes a system lifetime of 30 years, a capacity factor of 75%, a discount rate of 10%, and an insurance rate of 0.5% per year, so that the annual capital charge rate is 11.1%.
9. Assumes labor costs typical for a developing country, corresponding to an hourly wage of $0.48/hr. Total labor cost accounts for two attendants at all times earning salaries of 3000 Indian rupees (equivalent to $83) per month [Sridhar, 1997]. In industrialized countries where labor is significantly more costly, it may be economical to automate the biomass feeding process and/or design units of larger capacity to reduce labor costs.
10. Assumes a feedstock price of $1.50 per GJ, expected to be appropriate for plantation biomass.
11. Assumes annual maintenance costs are 3% of capital cost and overhead costs are 65% of maintenance costs [Wyman et al., 1993].

bine, for which acceptable costs and efficiency are only attainable at much larger scales.

3. System efficiency

The fuel cell accounts for approximately three-quarters of the generated power (149 kW) and the gas turbine one-quarter (50 kW, net of the compressor requirements). The total system efficiency of the baseline design was calculated to be 43.4% (AC electrical output divided by the higher heating value of the biomass feed). The sensitivity of this efficiency to variations in each of the key performance parameters was explored. If the turbine inlet temperature is increased from the baseline assumption of 900ºC to 1000ºC, the efficiency increases to 44.9%. If heat is assumed to be recovered from the turbine exhaust with an effectiveness of 90% (the baseline assumption is 85%), the efficiency increases to 44.0%. If the gasifier cold gas efficiency is assumed to be 75% (the baseline assumption is 79%), then the system efficiency decreases to 41.2%.

4. Cost of electricity

The cost of baseload electricity from the SOFC/GT system is calculated to be approximately 5 (US)¢/kWh for a plant fueled with plantation biomass costing (US)$1.5/GJ and operated by workers paid typical wages for rural areas in developing countries (see Table 2). Electricity at this price might well be competitive with electricity from large centralized coal-fired power plants in many developing country contexts. The costs presented here are estimates for technology that is established in the market and mass-produced. Uncertainties in capital cost and performance are inevitable at this early stage in the development process. As an indication of the sensitivity of the cost of electricity to the capital cost, a ± $100/kW change in installed capital cost would result in a change of ± 0.17¢/kWh in the cost of electricity. Likewise, an increase of ± 3 percentage points in efficiency would result in a decrease of ± 0.09¢/kWh in the cost of electricity. (Hence, an improvement in efficiency of 1% can compensate for an increase in capital cost of about $18/kW.)

Like any village electrification program, biomass energy would contribute to rural development by providing electrical power for basic residential needs as well as cottage enterprises and agricultural equipment such as irrigation pumps. Before substantial rural electricity- intensive industrial consumers are established, urban demand centers might serve as a market for the competitively priced baseload electricity provided by this technology. The transmission of electricity from rural areas to urban demand centers should not increase the delivered cost of power by a prohibitive amount. Even in cases where grid extension has been deemed uneconomical for electrification of a particular rural area, it may nevertheless be economical if the electricity were transmitted *from,* rather than *to,* the rural area. Village electrification, which typically serves loads that are small and intermittent, is often expensive when accomplished via transmission of electricity from centralized plants, since transmission costs are strongly dependent on the total capacity of the transmission line and the capacity factor with which it is utilized [Sinha and Kandpal, 1991]. But for the export of baseload electricity to urban centers from rural areas, lines would be utilized at a high capacity factor, and therefore transmission would be much more cost-effective. Indeed, this is the configuration under which many remote hydroelectric installations and mine-mouth coal power plants currently provide power to urban centers.

The technology described here potentially offers a far-reaching role for biomass energy to play in spurring rural development, by enabling rural areas to generate income by attracting electricity-consuming industries and by exporting surplus electric power to urban demand centers. The export of biomass electricity can benefit rural communities by providing local farmers with a buyer for biomass energy crops. The cost calculations in this study assumed a biomass feedstock price ($1.50/GJ or about $30/dry tonne) that is sufficiently high to make the cultivation of dedicated energy crops profitable in many areas [Carpentieri et al., 1993]. Identifying those contexts in which biomass energy can contribute positively to rural development requires understanding on a regional basis the dynamics of income generation and its coupling to agricultural production and distribution.

5. Conclusion

The biomass power system described here could probably be commercialized within a decade. In addition to ongoing development efforts aimed at applications involving natural gas as a feedstock, further efforts are needed to develop these systems for use with biomass, including: testing SOFCs on biomass gas and establishing whether the proposed clean-up system (i.e., cyclone, quench, filter, and sulfur removal) provides adequate contaminant removal, optimizing the combustor for use with a very dilute fuel gas, establishing reliable start-up and shut-down procedures, developing process controls that account for potential fluctuations in feedstock quality and gas quality, and optimizing the plant design for given biomass feedstock type, moisture content, scale, cost of labor, and other site-specific variables. Developing, demonstrating, and bringing this small-scale technology to the market by "buying down" the price of early installed systems is likely to require modest financial resources compared with what is required for large-scale centralized power generating technologies [Williams, 1997; Penner et al., 1995]. ■

Note

1. All efficiencies presented in this paper are on a higher heating value basis.

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