16
OPEN-TOP WOOD GASIFIERS

H.S. MUKUNDA
S. DASAPPA
U. SHRINIVASA

The technology and economics of a new class of open-top gasifiers for use with diesel engines in dual-fuel mode are described. The performances of systems that range in capacity from 3.7 to 100 kilowatts are discussed, with special emphasis placed on gasifiers at extreme ends of the capacity range. The essential differences and benefits of the new technology are compared with World War II closed-top models. Studies indicate that the open-top design achieves diesel replacement values greater than 80 percent and is less dependent on feedstock quality, moisture content, and density. The amount of diesel fuel saved per system among motivated users (mostly small farmers) exceeds 70 percent. A comparative analysis of two gasifier systems: a 5 kilowatt system that runs the village power station in Hosahalli, Karnataka (India), and a 100 kilowatt system that powers a sawmill on the remote island of Port Blair in the Andaman and Nicobar archipelago was undertaken. The cost of installing the larger system, including computerized data acquisition and control systems, was U.S.\$625[1] (Rs 12,500) per kilowatt, with an energy cost of \$0.074 (Rs 1.60) per kWh (the cost of energy subsidized by the state is Rs 1.25 per kWh).

INTRODUCTION

Solar energy captured by photosynthesis and stored in biomass can be converted by the process of gasification into a gaseous high-energy fuel (9,600 megajoules per m^3) that can be used in internal combustion engines for power generation. Gasification is a two-stage process: during the first stage, the biomass undergoes partial combustion to produce gas and charcoal; during the second, the charcoal reduces the product gases (chiefly carbon dioxide and water vapor) to form carbon monoxide (CO) and hydrogen (H_2). The process also generates methane and other higher hydrocarbons depending on the design and operating conditions of the gasifier.

1. 1 U.S.\$ = 20 Indian rupees at the time of preparing this paper (April 1991).

The combustible gas so produced is composed of about 18 to 20 percent H_2, 18 to 20 percent CO, 2 to 3 percent methane (CH_4), 8 to 10 percent carbon dioxide (CO_2), with nitrogen making up the rest. The gas will fuel a spark-ignition engine, delivering about 60 percent of the power of gasoline, or it will run a compression-ignition engine in dual-fuel mode, eliminating the need for 75 to 85 percent of the diesel fuel. The latter application is attractive for developing countries, especially India, where large numbers of diesel engines are employed at various power levels.

Wood gasification has developed in spurts, the most intense activity taking place during World War II in response to petroleum shortages in both civilian and military sectors. Some of the most insightful studies of wood gasifiers during this period are well documented [1, 2]. Most subsequent work has been devoted to the replication of existing systems. Around 1980, T.B. Reed and his colleagues at the Solar Energy Research Institute (now the National Renewable Energy Laboratory) in the United States conducted systematic laboratory studies on an open-top reactor, a version of which had been previously and successfully adapted for rice-husk gasification in China [3]. Recent research and development efforts have produced a technology that can process wood at powers ranging from 5 to 100 kilowatts.

Problems with open-top reactors frequently cited in the literature include the buildup of tar and the lack of critical assessment of available designs. Although different designs are described, they often are not rated against one another in terms of their overall performance [1]. Consequently, many designs that differ from one another only slightly have been proposed. Attempts have been made to rate the various designs according to the amount of time needed for pyrolysis (the release of volatiles in the presence of heat) and the reaction time of charcoal with air [4]. Although some studies have produced relevant findings, the results have not found their way into prototype designs as expected [1, 2]. Our chapter reviews the above studies and presents an integrated picture of gasifiers designed to run strictly on woody biomass. Research we have initiated on novel approaches to the gasification of agricultural wastes is beyond the scope of the present chapter.

THE OPEN-TOP VERSUS THE CLOSED-TOP GASIFIER

The World War II vintage closed-top and the more modern open-top gasifiers differ significantly in their geometries (see figure 1). In the closed-top gasifier, the hopper region, into which the biomass is loaded, is relatively massive, its size decided by two values: the reactor's diameter divided by its throat diameter (d_r/d_t) and the height of the hopper divided by the throat diameter (h_3/d_t), which are determined by the amount of time (typically 2 or 3 hours) needed to run a single, uninterrupted cycle (see figure 1). The choice of d_t reflects the need to balance two factors: the higher the value of d_t, the greater the risk that tar-laden gases will escape the high-temperature combustion zone, yet the smaller the value of d_t the greater the velocity of the gases that sweep through the throat and the reduction

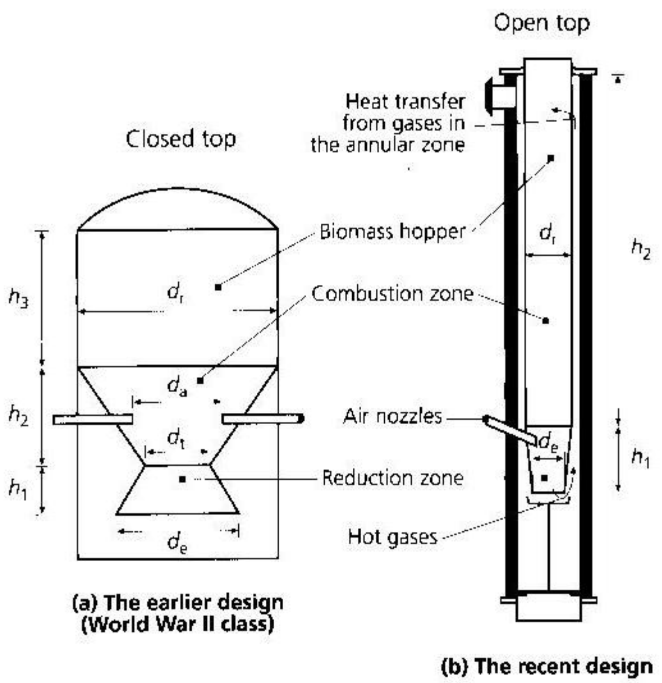


FIGURE 1: The most important dimensions in the closed-top reactor are the throat diameter, d_t, *the reactor diameter,* d_r, *the exit-plane diameter,* d_e, *and the relative heights of the reactor vessel,* h_1, h_2, h_3 *(see figure 1a). Correspondingly, the important dimensions of the open-top reactor are the lateral widths,* d_r *and* d_e, *and the heights,* h_1 *and* h_2 *(see figure 1b). Appropriate values for the ratios* d_r/d_t, h_1/d_t, *and* h_2/d_r, *are based on the "best" performance of some commercial designs.*

zones, collecting fine dust and ash. Tar is reduced in the smaller open-top model principally because temperatures in the reactor are higher, which facilitates tar cracking (the reduction of complex hydrocarbons into simpler forms), as well as the completion of all reactions.

Another drawback to the closed-top gasifier is that the diameter of the hopper is so large that heat transfer from the high-temperature zone generally affects wood chips near the hopper's wall rather than in its center [5]. The problem is overcome in models, most notably the Imbert generator, that have an outer chamber around the hopper. Hot gases flowing along the outer wall transfer heat to the wood chips. In some cases, preheating the air is recommended [1], but this is generally ineffective because of the low heat capacity of air and the large area required for heat transfer.

Other closed-top designs, such as the monorator [1], include an outer zone next to the hopper for tar collection. Unless tar is reduced, the walls become laden with tar that is either encrusted and hard, or liquid and sticky. Tar in the latter state may form glue-like bridges, particularly when the gasifier is started, thus interfering with the flow of biomass. Another drawback to the closed-top gasifier is that generating combustible gas of reasonable quality is more difficult when wood with a high moisture content (20 to 30 percent) is used. This problem is one that cannot be entirely attributed to the moisture content of the wood and can be solved by installing a properly designed hopper. Because of these problems and the need to address them, the closed-top gasifier is considered less effective than the open-top model.

Tar can be reduced by distributing air nozzles around the periphery of the reactor. In this way fuel vapors are intercepted and combusted. During this process temperatures in the combustion zone also rise, which helps reduce tar [2]. The number of air nozzles is determined by the desired flow rate (and level of thermal and mechanical power). Air distribution around the nozzles, and in regions between the airflow zones where volatiles can escape (resulting in high-tar gas), can be mapped. Early gasifier programs in many countries encountered difficulties, in large part because inadequate attention was paid to tar problems. A key problem is that once tar escapes from the reactor, it cannot be readily eliminated because the cooling/spraying systems that are effective against dust do not trap tar-laden vapors. Thus, tar is best eliminated through thermodynamic and oxidative measures in the reactor itself.

The open-top gasifier, on the other hand, provides for more homogeneous airflow because the gases pass through a long porous bed of fuel in the vertical reactor [6]. Studies to determine flow distribution under cold conditions [6] indicate that the velocity distribution in a packed bed is homogeneous after a few particle depths. In addition, regenerative heating created by the transfer of heat from the gases (through the wall) to the biomass increases residence time in the high-temperature zone and thus leads to better tar cracking. Many of the configurations of the open-top design, including laboratory models [4], lack the air nozzles used in earlier designs. A commercial version developed by W.P. Walawender and his colleagues at Kansas State University [7] has a complex central air-nozzle that helps reduce tar, but does not facilitate start-up of the system. However, by combining the open-top with an air nozzle across the reactor, quick lighting with a simple wick flame is possible. In addition, the air nozzle stabilizes the combustion zone, preventing stratification, which occurs when the flame front moves in an opposite direction to the airflow. As a consequence, the high-temperature zone spreads above the air nozzle by airflow from the top, rather than by radiation, thermal conduction, and weak convection processes, as is the case with the closed-top gasifier (see figure 2).

Forced convection heat transfer from hot gases flowing in the annular gas passage (see figure 1) also contributes to upward flame propagation in the open-top. Such enhanced heat transfer makes it possible to gasify wood chips that have a moisture content as high as 25 percent because the added heat reduces the extra moisture. In general, air drawn through the top of the gasifier represents about 40 to 70 percent of the total inflow, depending on the size of the wood chips and rate of gas flow, which can reduce pressure along the path. Reliability is greatly en-

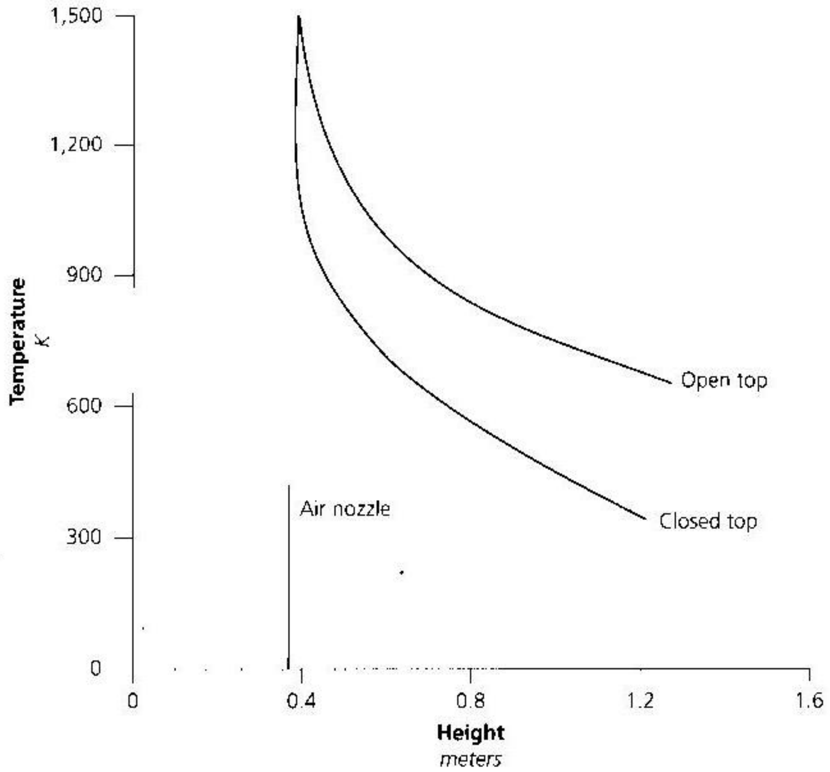


FIGURE 2: The graph shows the temperature variation from the air nozzle region in the classical closed-top and the present open-top design. It is clear that the width of the high-temperature region, 600 K and above, is about 1 meter for the open-top design, whereas it is constant at about 0.4 meters for the earlier design. What is more, it can be controlled by decreasing the airflow through the air nozzle in the current design.

hanced by the ability of the reactor to dry wood chips that contain variable amounts of moisture; insulation around the reactor helps maintain high temperatures in the reaction zone and thus also helps to reduce tar.

Wood-chip size also affects the reactor's operation. Studies indicate that to achieve power levels of 15 to 75 kilowatts, chips should be from 60 to 80 millimeters long and from 50 to 60 millimeters in diameter [2]. For open-top gasifiers, maximum size of the wood chip should be about one-sixth to one-seventh the diameter of the reactor in order to meet flow requirements, without prolonging gasification time [4] or creating excess porosity.

The actual conversion of the biomass to gas is a two-step process. The first step, called the flaming period, occurs when biomass burns in the presence of air drawn largely from the top, producing charcoal. The second step, known as charcoal conversion, occurs when charcoal reacts with carbon dioxide and water vapor to produce combustible gas. The duration of both stages has been determined by laboratory studies on cubes of wood [8]. The results, which are correctly expressed

Table 1: Reactor diameter and related parameters for various power levels

Power	Gas flow rate	Air flow rate	Air flow rate from top		Wood consumption rate	Diameter	Air flux
kilowatts	*g/second*	*g/second*	*g/second*	*percent*	*kg/hour*	*millimeters*	*kg/m²/s*
3.7	2.5	1.9	0.76	40	3.8	150	0.043
20.0	15.0	9.5	4.80	50	20.0	250	0.100
100.0	70.0	42.0	21.00	50	100.0	350	0.210

as volume-based diameters, apply to other geometries, such as cylinders and spheres, as well. Although the time needed to convert charcoal into CO and H_2 with CO_2 alone has been quantified kinetically, the effect of H_2O, which drives the conversion faster than CO_2 does, seems to have been ignored. The situation deserves further attention.

For a reactor of any diameter, the optimal height is determined by the properties of the woody biomass, namely, its density, specific heat, and heats of phase-change according to a simple model for heat balance. The distance, or height, traveled by the woody biomass must allow for a residence time at least equal to the sum of the flaming pyrolysis and charcoal conversion times. Thus, open-top gasifier designs can be based on a one-dimensionality consideration for which the ratio of height to diameter of the reactor should be large, typically a value from six to eight. Therefore, once height is determined, diameter can be calculated. Smaller diameters are generally preferred in order to minimize reactor size and maximize heat transfer to the entire cross section. Too small a diameter, however, necessitates the use of smaller wood chips and leads to unmanageable pressure drops at reasonably high flow rates. Such factors must be optimized, although at present there are no precise guidelines for doing so (see table 1).

The superficial mass flux (the flow rate of gas relative to area) of air drawn from the top of the reactor is shown in column 8 of table 1. As power increases (column 1), mass flux increases, a relation that reflects the reactor's more compact design. Increasing the diameter at higher power levels (for example, to maintain the same mass flux as for 3.7 kilowatt system) will not hinder performance, provided the reactor height is sufficient to allow for chemical reaction time. Diameters with a length-to-diameter ratio equal to 2 or 3, however, lead to the loss of one-dimensionality; consequently, the reactor's center may not receive as much heat as its perimeter, where heat transfer results in better flaming pyrolysis. The 3.7 and 20 kilowatt reactors are equipped with a single air nozzle; the 100 kilowatt system has six, which reflects its larger diameter. Thus, if the diameter size of the 20 kilowatt system is to be increased, additional air nozzles may be needed.

Height and volume requirements can be related mathematically as follows, with the velocity of movement of the wood chips v_w expressed in terms of the

mass consumption rate of wood chips $\dot{m}_w$, the superficial density of wood chips, ρ_{sup}, and the cross-sectional area of the reactor A_r as

$$v_w = \frac{\dot{m}_w}{\rho_{sup} A_r} \qquad (1)$$

If one assumes that the wood chips undergo heating and flaming pyrolysis during their passage from the top of the reactor to the air nozzle, this time t_f can be expressed as the diameter of the wood chips d_w (which can be a mean diameter, if based on volume, or simply a diameter if the wood chips are long and cylindrical) as

$$t_f = K_c d_w^{1.8} \text{ where } K_c = 3.5 \text{ s mm}^{-1.8} \qquad (2)$$

where d_w is in millimeters and t_f is in seconds. The above equation is indicative of the diffusion limits of the flaming pyrolysis process; the exponent on d_w, which is derived from simple theory, works out to be 2. The value of 1.8 is a curve fit of laboratory data [9] that compensates for the influence of convection currents. The height of the reactor above the air nozzle h_2 is obtained as

$$h_2 = v_w t_f = \frac{4K_c}{\pi} \cdot \frac{\dot{m}_w d_w^{1.8}}{\rho_{sup} d_r^2} \qquad (3)$$

In the above equation K_c is about 3.5 seconds mm$^{-1.8}$ for d_w up to 25 millimeters. Although wood chips are about one-sixth to one-seventh the diameter of the reactor, they undergo a size reduction of 10 to 15 percent [9] during flaming. Moreover, those that are larger than 25 millimeters in diameter have a tendency to crack into smaller pieces. For much larger reactor sizes, the wood-chip size reaches an asymptotic limit caused by the availability of biomass sizes. In such cases, the height of the reactor decreases with the square of the reactor diameter. Height h_1 is governed by the reduction reactions of charcoal with CO_2 and H_2O.

As the above calculations indicate, reactor designs have a rational basis; nevertheless, it has not been possible to generate a design that will meet a target final composition under a given set of operating conditions. In order to do so, more work on basic kinetic parameters and modelling needs to be done.

THE MODERN OPEN-TOP GASIFIER

The reactor and gas-cooling and -cleaning systems are the most important components in an open-top gasifier (see figure 3); an additional feature is the auxiliary wood-processing system. A variety of designs, which were motivated by the need to adapt systems to individual site conditions, now exist. Some designs are retro-

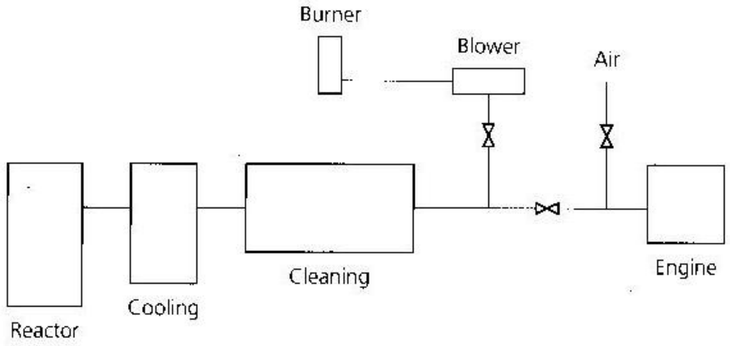


FIGURE 3: Block diagram of the elements of the gasifier system.

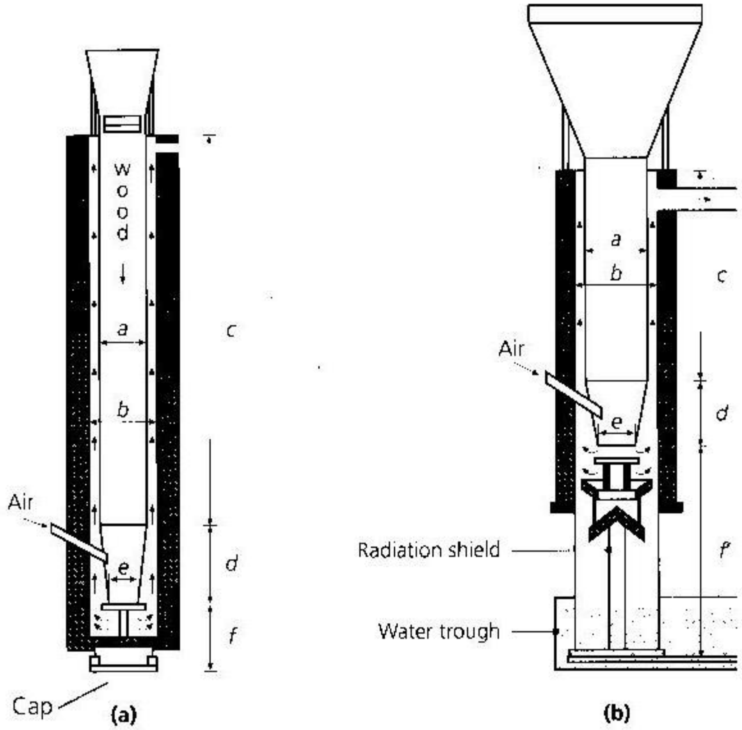
fits of existing systems; in others, the major components have been redesigned, as described below.

The reactor

We have proposed two reactor redesigns (see figure 4). In both, the annular stainless-steel reactor is wrapped with 75 millimeter light alumino-silicate insulation and encased in an outer aluminum sheet. The inner shell tapers to a cone at its bottom to create a small, intense combustion zone and to facilitate ash removal by high-velocity gases. In one design, the bottom is capped, which is useful where conditions do not allow for additional space in the bottom region. However, the maximum uninterrupted run for a bottom-capped 3.7 kilowatt system is 17 hours and about 10 hours for a 100 kilowatt system at 80 percent load. Continuous operation is possible with the alternative design, which is equipped with a water seal that enables the ash to be washed away by the water, thus obviating the need to interrupt the system for cleaning. Although water evaporation through the seal caused by radiant heat transfer from the reduction zone was a problem initially, a radiation shield has since been designed [10] that has enabled the seal to function satisfactorily at all power levels.

Cooling and cleaning systems

After a 10-year effort, a number of effective gasification cooling and cleaning systems have been designed, all of which had to first overcome a number of constraints: cooling had to make minimal demands on the local water supply, the dust extractor had to be available for a low price, and the time between overhauls had to be comparable to that for the engine itself. These constraints have now been met for dry and wet cooling systems, both of which can meet the requirements efficiently. Whereas wet cooling systems recirculate and spray water through a cooling tower (see figure 6), dry cooling systems dissipate the heat through large-area metal surfaces. Both depend on cleaning systems that use coir (coconut fiber) mats, cloth filters, and sandbed filters to cleanse the gas of partic-



Capacity kilowatts	a	b	c	d	e	f	f'
	dimensions in millimeters						
3.7	150	180	1,200	250	80	500	250
20	230	300	1,650	350	145	600	300
100	350	450	2,800	500	250	850	500

FIGURE 4: Two reactor redesigns have been proposed. In one (a) the bottom is capped; in the other (b) the bottom is set in a trough of water.

ulates, and both reactors, fortunately, produce little tar; the small amount generated is carried into the engine without being deposited in the passages, and thus poses no operational difficulties [11].

The 3.7 kilowatt gasifier

After leaving the reactor, the gas enters the cleaning system, which in the 3.7 kilowatt gasifier is a high-efficiency cyclone: a centrifugal device that extracts fine particulate matter. Coarser particles are left behind in the annular region of the reactor itself (see figure 5). The gas then enters a long vertical tube tangentially so that it spirals down to a water trough at the bottom of the tube. There the gas skims across the water's surface and enters a second vertical tube, again tangentially. The tangential movement facilitates heat transfer from the gas to the wall. At the end of a typical six-hour run at a load of 3 kilowatts, the temperature of

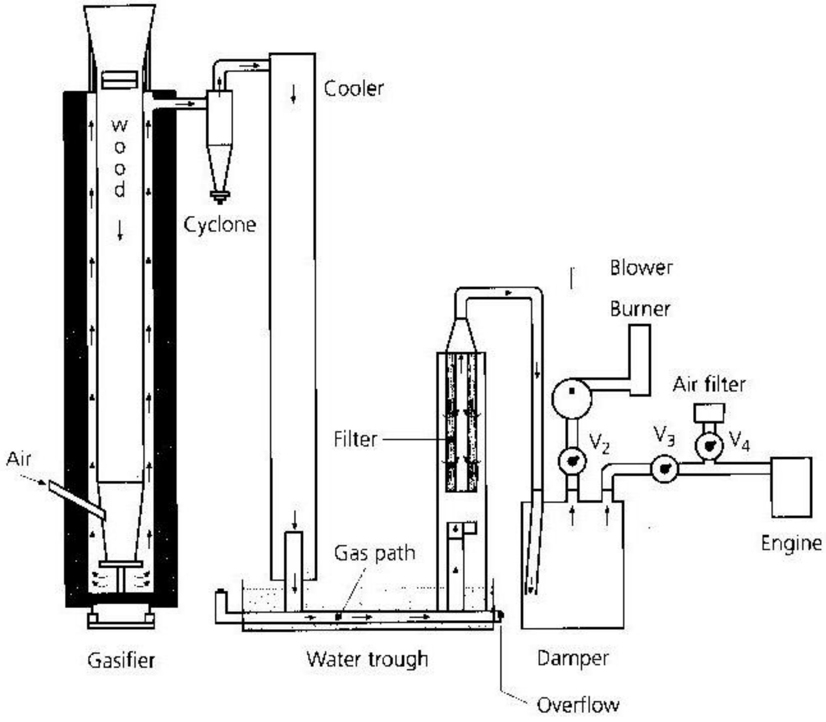


FIGURE 5: The 3.7 kilowatt system with dry cooling facility.

the gas entering the cyclone is about 600 K; when it leaves the cyclone it has reached 400 K; by the time the gas enters the vertical tube containing the filter, it is near-ambient temperature. The cooling raises the density of the gas and the mass flow of the charge ingested by the engine.

The choice of a water seal for the wet-cooling reactor (see figure 6) is somewhat incidental, since both developments took place around the same time. It is possible to combine the bottom-cap reactor with the water cooling system. The gas enters a long vertical tube at the top where a spray nozzle is mounted. Water, which enters the sprayer from the pump outlet and is controlled by either the size of the tube or by a valve, mixes with the incoming gas, cools it, and removes a major portion of the fine dust. The fine mist of dust and water vapor is eliminated when the gas passes through the cyclone. Measurements have shown that dust and tar levels at this stage are low, but an additional filter of sand and coir pith is nonetheless recommended. A pressure drop of about 400 pascals occurs in the reactor and another of 1,000 pascals occurs in the cooling and cleaning system, amounting to a total pressure drop of about 1,400 pascals; only when the pressure drops by more than 2,000 pascals will blockages affect performance by reducing the diesel replacement.

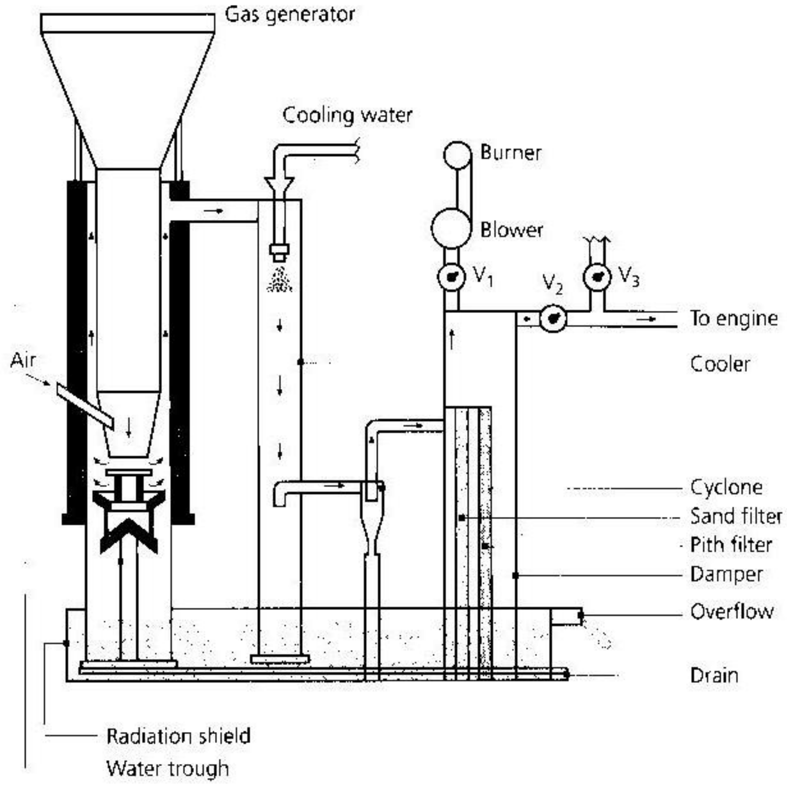


FIGURE 6: The 3.7 kilowatt system with water cooling facility.

The 100 kilowatt gasifier

The cooling and cleaning system of a 100 kilowatt gasifier differs from a 3.7 kilowatt system primarily because cooling occurs in two stages (see figures 7 and 8). The two stages reflect higher (about 30 kilowatt) cooling requirements, but are convenient to implement. Cleaning is performed by a 100 millimeter thick, 1.2 m^2 cross-section sandbed consisting of particles ranging in diameter from 250 to 600 microns. A 100 millimeter thick bed of coir pith absorbs residual moisture. Pressure drops by 600 pascals as the gas crosses the reactor and by 1,200 pascals as it crosses the cooling and cleaning system.

Blower, valves, and burner

Once the gas is cooled and cleaned, it passes through a damper either to a burner or to the engine air inlet. The damper isolates the engine from pressure fluctuations in the gasifier and helps to increase induction efficiency. One branch from the gas line passes through a valve to the blower, which is either hand cranked or electrically driven, and then goes to the burner, which is a simple cylinder with tangential entry for gas at its base (see figure 5). The design differs from earlier

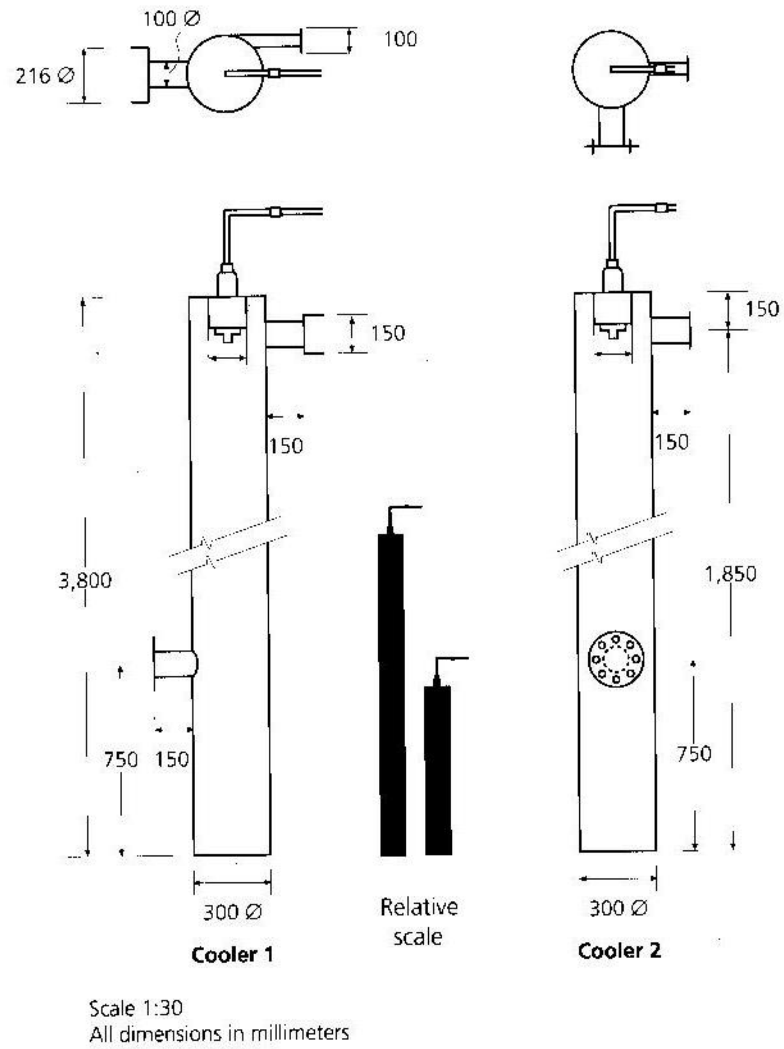


FIGURE 7: The cooling and cleaning system for a 100 kilowatt system.

designs in the flares—tubes in which the gas is burned—and benefits from increased flame stability. Because the flame length is short, it is unaffected by wind currents. A second branch of the gas line is linked to air to permit the engine to draw the gas–air mixture.

The gasifier is started with a blower and runs until combustible gas is obtained, at which time the engine is cranked and made to run for a few minutes on diesel or gasoline before the gas line is opened. Because the gasifier is loaded with charcoal to some 300 millimeters above the air nozzle, it functions more like a simple charcoal gasifier in the early stages. Some users start the gasifier by running the engine directly, drawing air through the gasifier itself during the early stages.

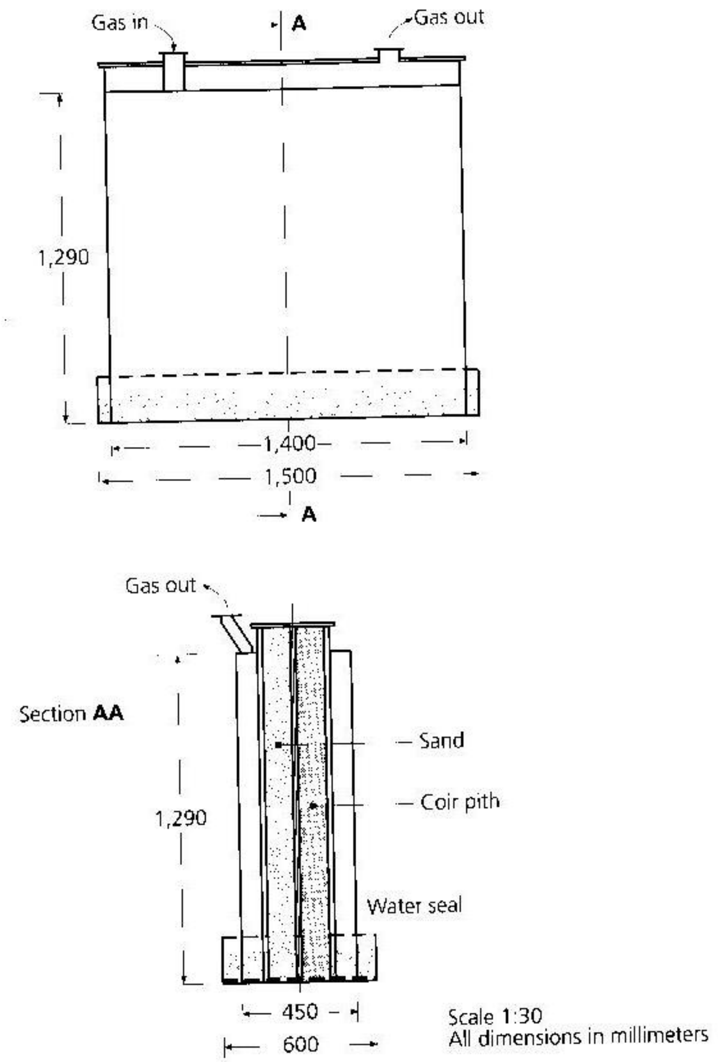


FIGURE 8: The cooling and cleaning system for a 100 kilowatt system. A frontal view is presented (top); as well as a cross-sectioanl view (bottom).

The air is then subsequently replaced by gas. Such a strategy renders use of the blower redundant in small power systems (those 3.7 kilowatts in size or less).

The wood-processing system

The woodstock available to users of 3.7 kilowatt systems varies. Some comes from the green and tender stems of mulberry plants after the leaves have been stripped to provide fodder for silkworms. The stems, which are from 10 to 15 millimeters in diameter, are easily chopped into pieces that are from 20 to 30 millimeters

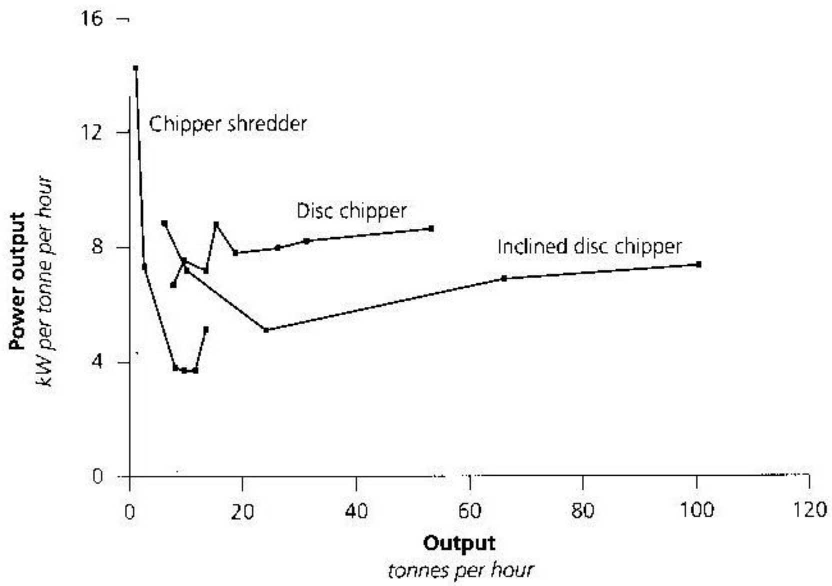


FIGURE 9: The power (kW) per tonne per hour of wood chips relative to ouput of woodchipping machines.

long. Other woodstock comes from dead or old trees that are from 50 to 70 millimeters in diameter and cut into pieces that are 1 or 2 meters long. In the latter case, the wood must be cut with a 0.75 kilowatt electrically driven circular saw in a separate cutting and sizing facility. Such a saw can process 40 kilograms of wood per hour, which is adequate for most applications below the 20 kilowatt level.

The 100 kilowatt system runs on wood chips that are from 25 to 30 millimeters in diameter and from 50 to 70 millimeters long. One such gasifier has been installed at the Chattam Island sawmill as part of a demonstration program run by India's Department of Nonconventional Energy Sources (DNES). Although some of the wood, which ranges from 100 to 200 millimeters in diameter and from 400 to 600 millimeters long, is light, most is dense and hard. The tree species processed at the sawmill include padauk (*Pterocarpus dalbergiodes*), mowa (*Maduca indica*), and garjan (*Dipterocarpus indicus*). Most wood wastes are of high density (900 kilograms per m^3), but some are of low density (450 kilograms per m^3). Although the mass consumption rate of both types of waste is the same, lower-density wood must be consumed volumetrically faster, and thus must be processed by a taller reactor.

The wood waste is transported manually to the gasifier plant from the mill and then fed through a chipping machine. In searching for appropriate chipping machines for the demonstration site, we found that most equipment, including inclined disc chippers, chipper shredders, and ordinary disc chippers is manufactured in Europe. Technical information on the power needed to produce a certain tonnage of chips each hour was put together from the brochures (see figure 9).

The power per unit output (1 tonne per hour) rises sharply, reaching 15 kilowatts for smaller loads of 500 kilograms per hour, but then asymptotes to about 8 kilowatts for loads larger than about 20 tonnes per hour. To produce about 250 kilograms per hour of chips requires a machine having about 5 kilowatts of power. At the Port Blair sawmill, a 20 tonne hydraulic power press with a 3.7 kilowatt capacity motor was modified to operate a hardened spring steel blade with its cutting edge angled to facilitate slicing. Trial runs show that the machine can easily cut about 200 kilograms per hour of wood. Chip preparation facilities, however, should be custom designed for each site; in some situations, for example, cutting machines that have a 3 kilowatt circular saw are adequate for sizing the wood.

The chip-loading system

Wood chips are loaded manually into both the 3.7 and 20 kilowatt systems. Every 30 and 45 minutes, loads of 2.5 and 10 kilograms, respectively, are emptied into the reactors' hoppers. In larger gasifiers, such as the 100 kilowatt system, a machine-driven loading system is necessary (see figure 10). When the chips drop below a certain level, the operator activates a conveyor belt that carries a new supply to the top of the gasifier. The arrangement, however, takes up considerable floor space, adding to the system's initial costs. Efforts are therefore being made to develop a more economical system. One possibility is split-level flooring: by constructing a platform about 1 meter below the top of the gasifier, a few bags of wood chips can be loaded into the reactor in about half an hour, thus eliminating the need for a conveyor belt.

Instrumentation and control

The diesel tank of the 3.7 kilowatt gasifier is equipped with a bypass valve and a measuring cylinder. By measuring diesel-flow rates in this way, the performance of the diesel engine can be compared in diesel-only and dual-fuel modes. Initially both gasifier systems were provided with a manometer to measure total pressure drop; if the drop was excessive, the system could be shut down for maintenance. Field observations, however, indicate that the manometer is almost never used; the systems run until a breakdown occurs and then they are dismantled for maintenance. During operation, diesel flow is optimized by reducing airflow to the engine, which increases gas flow and thus energy flow. If diesel flow becomes excessive, maintenance of the system becomes necessary. The diesel governor on the engine maintains steady operations until a decrease in airflow signals a fuel-rich condition in the dual-fuel mode and the engine cannot take the load. Airflow is then reduced only enough to support the load with a high diesel replacement. Typically, the stall region occurs when diesel replacement exceeds 90 percent; therefore, the system can be run in a stable manner at diesel replacements in excess of 85 percent, but below 90 percent.

The 100 kilowatt gasifier is fitted with a fair amount of instrumentation, some of which was specifically developed for the system. Voltage, current, frequency, and diesel flow rates are recorded. When the system operates in the dual-

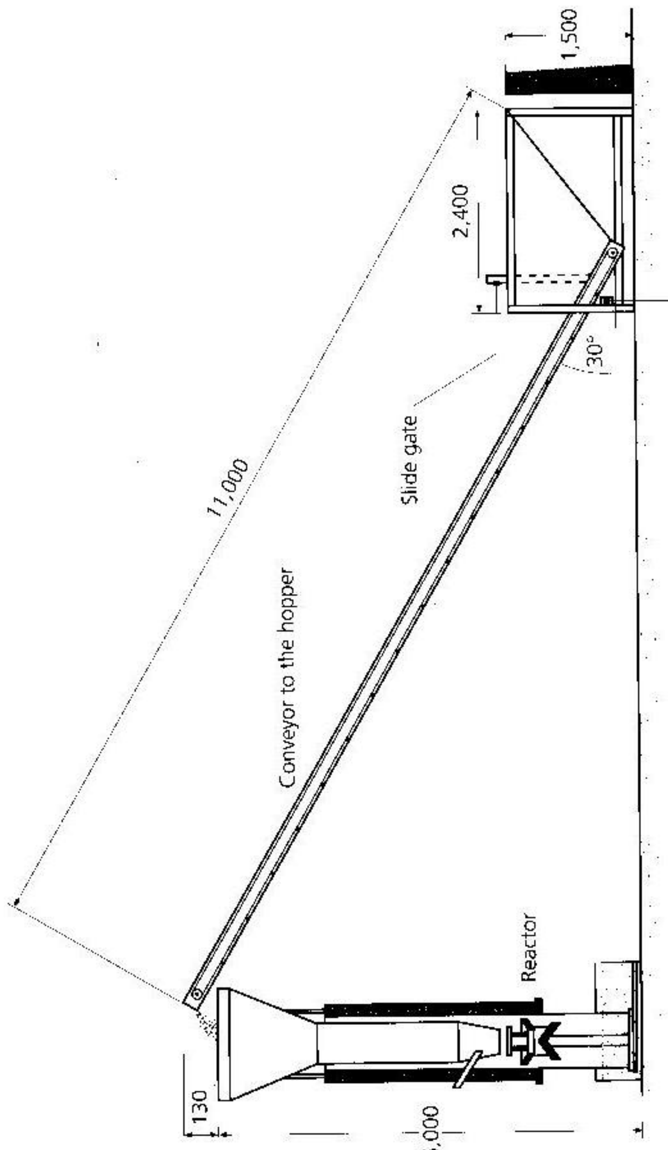


FIGURE 10: The wood chip loading system for a 100 kilowatt gasifier.

Table 2: Tar and particulate levels

Flow rate *g/second*	**Tar** *ppm*	**Particulates** *ppm*
3 (3.7 kilowatt system)	30–40	50
40 (100 kilowatt system)	30–40	50

fuel mode, diesel consumption is reduced by decreasing airflow, thus increasing gas flow. Steady operating conditions are maintained by increasing resistance in the air line, which can be quickly reversed if the engine is unable to cope with the large demand near full-load conditions.

Frequency is measured electronically with a 0 to 10 millivolt sensor. The change in the wire's resistance resulting from the flow of diesel fuel is converted to an output signal with the help of appropriate electronics. After extensive calibration and the installation of high-performance electronic components, the measurement unit for the 100 kilowatt gasifier seems robust and accurate in its performance. Moreover, the system has now been linked to a personal computer, which continuously records the operating data and provides instructions to the control system for corrective action during the run.

Performance of the gasifier–engine system

Gasifier performance was measured initially by running it with a blower at various flow rates. Gas quality was assessed by measuring its composition, calorific value, and tar and particulate levels (see table 2). Engine performance in dual-fuel mode provided diesel replacement data at various loads. Apart from this, some monitoring of the engine's condition, including examination of its lubricating oil, valve seating, and engine head, were also made. Long-term monitoring of engine condition is on-going in Hosahalli, a small village in India, where a 4.4 kilowatt engine coupled to a 3.5 kVA alternator is being used for electrification. In addition, DNES had the system rigorously tested at a national testing center at the Indian Institute of Technology in Bombay before initiating its large-scale implementation. Most of the results obtained by the authors have been confirmed by tests carried out by P.P. Parikh and her colleagues at the Institute [11].

Every internal combustion engine can accept a certain amount of dust, but dust levels must not be excessive. Gasifiers produce dust in the form of fine carbon and tar, which if deposited at bends and valve seatings can cause engine seizure under extreme conditions. Therefore, the levels of both must be routinely measured. Tests on the relation between flow rate and the production of tar and particulate matter show that if the gas has a calorific value of 5 or 6 megajoules per cubic meter and a methane content of 1.5 to 3.0 percent, then tar and particulates will measure less than 40 and 50 ppm respectively. Shifting from diesel to dual-

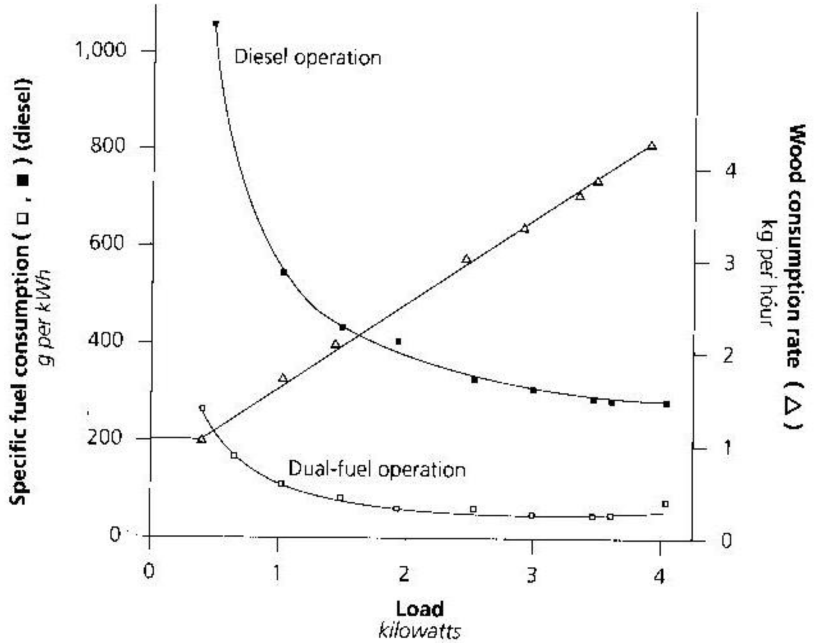


FIGURE 11: Diesel consumption in diesel-only and dual-fuel run with load for a 3.7 kilowatt system in electrical mode.

fuel mode is smooth; reducing the airflow raises the diesel replacement level to 85 percent or more at all loads. Fine tuning the air valve raises the replacement value still higher, to 93 percent. Minimum specific fuel consumption occurs at 80 percent load and is about 285 grams per kWh (see figure 11). In a normal cycle, with some variation in load, diesel fuel is consumed at a rate of 300 grams per kWh; maximum electrical output is 4 kilowatts. In the diesel-only mode, overall efficiency of the system is 28 percent. In the dual-fuel mode, efficiency drops to 15 percent, a situation that is related in part to the reduced combustion efficiency of the engine cylinder, which results from the lower flame speed of the wood gas–air mixture.

In the dual-fuel mode, lubrication oil needs to be changed about half to three-quarters as often as in the diesel mode. Also, the engine head is not affected until after about 1,200 hours of operation. But piston rings had to be replaced after about 1,600 hours, in part a result of overloading the engine.

DEMONSTRATION PROJECTS

The 3.7 kilowatt gasifier system has been turned over to private industry, and under a DNES program more than 300 such systems have been disseminated to beneficiaries, mostly in rural areas. Studies of dissemination, user motivation, and field performance have been carried out by the Karnataka State Council for Science and Technology, DNES, and the authors [10]. Two of the study's findings are particularly significant: first, users find the open-top system easier to operate than the classical closed-top model and second, mean time between maintenance and failure has increased [10].

The Hosahalli project

An open-top gasification system has been deployed since 1987 in Hosahalli, a village located about 110 kilometers southwest of Bangalore that has 43 houses and a population of about 270. The project, which is supported by various government agencies, was conceived as a way to provide rural villages with energy services derived from biomass. Hosahalli was chosen for a number of reasons. It was one of 13 villages in the state of Karnataka that had yet to be electrified, it had nearby land that was suitable for biomass generation, and it had a government willing to convert the land to biomass plantation and to construct a small power station.

Two and a half hectares were provided for biomass plantation and 60 m^2 of land were made available for the power station. The state electricity board helped draw electrical lines throughout the village. Each house was given one 40 watt fluorescent lamp and one 15 watt incandescent lamp; six 40 watt tube lights were provided for street lighting. An early version of the open-top gasifier with a dry cooling system and a single phase 3.5 kVA gasifier-based engine was installed to meet a total electrical load of 2.6 kilowatts.

The project was implemented in a series of stages. The first phase was initiated with the planting of such species as *Leucaena luecocephala, Acacia auriculiformis, Delbergia sissoo, Eucalyptus,* and others [12], and was completed when the plantation began to yield 10 tonnes per hectare of dry woody biomass in the first year and 7 tonnes per hectare in subsequent years. In May 1988, villagers received the first flow of electricity, which was provided for four hours every day during the first eight months and thereafter for six hours every day.

The second phase was initiated in response to a demand for drinking water, which at that time was obtained from a tank about half a kilometer from the village. The tank would dry up toward the end of December, creating significant water shortages during the four months before monsoon season. A decision was therefore made to pump deep-bore well water into two tanks inside the village. A 3 kilowatt pumpset was installed, which enabled the water to be piped over a distance of 500 meters. The pumping station, which is run by a second gasifier, has been operational since September 1990. Two village boys operate the gasifier, cutting tiny tree branches to size, drying them in the sun (or in a specially designed dryer that connects to the engine's exhaust pipe), and then loading them in the gasifier. When branches are unavailable the boys use a 0.5 kilowatt circular saw to split and cut logs. During monsoon months the dryer is necessary [10].

During the 15 month operating period from June 1988 to August 1989 [13], the amount of diesel fuel saved equaled 72 percent of the diesel-only mode and the 6.4 tonnes of wood burned (see figure 12) was far below the plantation yields

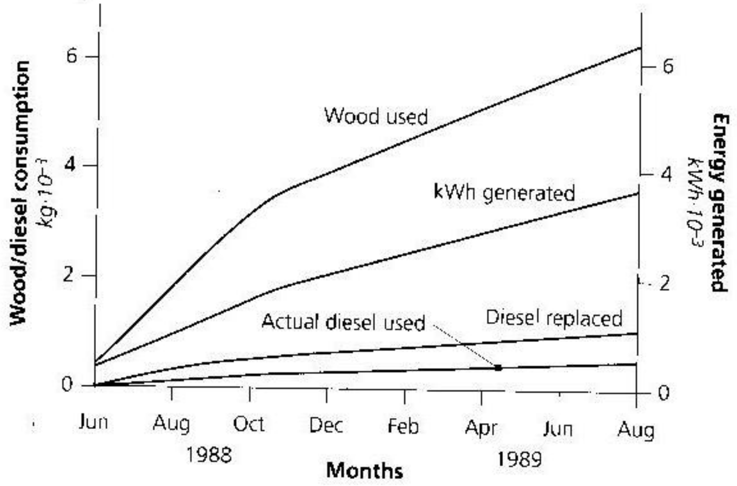


FIGURE 12: Energy delivered measured in terms of diesel and wood consumption during 15 months of open-top gasifier operation at Hosahalli.

of 25 and 15 tonnes. Electricity has reduced kerosene consumption for lighting purposes by an estimated 0.95 tonnes in one year [14]. The next stage calls for the construction of a flour mill with management of the system transferred to a village council.

The Port Blair sawmill project

A 100 kilowatt open-top system has been running a sawmill in Port Blair since January 1990. During daily use the engine delivers 50 kilowatts of lighting and from 10 to 27 kilowatts of power for welding and machining operations. The engine, which runs at diesel replacements of 76 to 85 percent, seems to have no difficulty handling the load. Minimum specific fuel consumption is 260 grams per kWh for loads ranging from 45 to 70 kilowatts. In diesel-only mode, overall efficiency increases to 34 percent, whereas in dual-fuel mode (with wood consumption at about 1.0 kilogram per kWh), overall efficiency drops to between 24 and 26 percent [15]. The gasification efficiency is about 85 percent, a value consistent with any well-designed gasifier.

Gasifier research and development continues. Recent efforts, for example, have resulted in a new ceramic reactor shell that can withstand the hostile, reactive, and thermal environment inside the reactor. The new shells, which are expected to significantly lengthen a reactor's life as well as improve its economics, are currently undergoing field trials.

OTHER FIELD TRIALS

Despite a lack of enthusiasm in the developed world for gasifiers as substitutes for petroleum fuels, research on them continues, motivated in large part by the desire to aid developing countries [16].

One open-top system, which was designed at Twente University in the Netherlands and installed in central Java, has a central air supply through the top, a refractory lined reactor and a rotating grate at the bottom. The system, which can generate 20 kilowatts of power, has run for more than 12,000 hours. Despite the fact that tar and dust in the treated gas reach levels as high as 2,000 and 130 parts per million (ppm) respectively, the system is said to have had no serious operational problems. No excessive wear on engine components was observed during overhauls that took place after 4,000 and 11,500 hours of operation. Studies indicate that although 70 percent diesel replacement was achieved, the annual average proved closer to 50 percent. Unfortunately, the annual diesel replacement level was assessed at greater than 70 percent in order for the gasifier to be economically viable.

One of the largest wood-gasifier plants based on the Imbert design is in Paraguay. The plant has three 420 kilowatt generators, which are powered by 1,000-rpm natural-gas engines and operate almost 7,400 hours a year. Of the power generated, about 56 percent goes for agro-industrial purposes; about 24 percent goes to households. The amount lost in transmission over an area of 240 km^2 is thought to be 20 percent. Reports do not indicate that performance of the control system is affected by a varying load situation, so it may be presumed that the control system was working satisfactorily.

The ferrocement open-top system [17] uses low-cost materials and fabrication techniques and so is relatively cheap to buy. Data show that the system cost is about $350 per installed kilowatt for a 5 kilowatt system. The system includes several large cylinders equipped with cloth filters, security filters, and a complex fabrication procedure for cleaning [17]. Despite the system's low cost, we believe it will have difficulty with air leakage, and thus may be unable to maintain diesel replacement levels of 75 to 85 percent. Although the design of the reactor itself may be of some value in terms of low cost, the total system is unlikely to succeed in the long term. It must be emphasized that in order to minimize leakage and render a field system reliable, the number of joints must be absolutely minimal. Another drawback to this design is that it runs on charcoal; the system's economy and user-friendliness would have been higher had it been designed for wood chips.

Chinese rice-husk gasifiers are also open-top designs [18]. The gasifiers produce gas that is high in tar because pyrolysis is the dominant process in these systems. Rice-husk char is far less reactive (by about one-tenth to one-twentieth) than wood charcoal, so char conversion and tar cracking normally do not occur in rice-husk gasifiers as they do in wood gasifiers.

Wood gasifiers have also been installed in Indonesia [19], but details of their performance have not been reported. Most of those systems are either pilot plants or demonstration projects. One pilot plant, which has a capacity of 80 kilowatts, produces gas that circulates upward through the biomass (in an updraft mode) and is reported to run 12 hours a day, generating electricity up to 65 kVA [19]. The system operates with a diesel engine, although the diesel replacement percentages have not been published. Power generation equivalent to 100 kilowatt systems is thought to be uneconomic.

In recent times, Imbert gasifiers with capacities that range from 50 to 500 kilowatts [19, 20] have been installed in several countries. In Guyana two gasifiers, with capacities of 60 and 125 kilowatts respectively, have run for approximately 12,000 hours in a sawmill; a third gasifier is expected to be added to them, increasing the system's total capacity to 4.8 megawatts. The investment costs of an Imbert plant is said to range from DM3,000 to DM4,000 ($900 to $1,100) per kilowatt of power output. Average wood consumption is about 1.25 kilograms per kWh, indicating an overall efficiency of about 18 percent.

SAFETY AND ENVIRONMENTAL CONSIDERATIONS

Exposure to carbon monoxide in the gas is of little or no concern because pressure in the system is below ambient levels—air can leak into the system, but gas cannot escape to the outside. At points where air leakage occurs and temperatures are high, burn-off at the reactor bottom may occur; in some instances of transient operation, pressure build-up from instantaneous combustion may create a potentially explosive situation. In early trials with closed-top gasifiers, such explosions did occur, but the problem has been eliminated in the current design, where pressure is released at one of the water seals with no untoward effect other than splashing of water.

In pumping applications, tar and dust, which are carried directly into the engine in a dry cooling system, are instead transported by the water of the wet cooling system and deposited on the ground, where they may pose an environmental hazard. Some countries, including India, regulate such discharges, quantifying them in terms of biological oxygen demand (BOD), chemical oxygen demand (COD), phenolic content, and other pollutants. Regulations are more stringent for discharge into inland surface waters than for isolated irrigation fields (see table 3).

The open-top gasifier produces BOD levels of 3.5 milligrams per liter, COD levels of 182 milligrams per liter and phenol levels of 12.0 milligrams per liter. The unacceptably high phenol levels should be reduced by constructing a filter bed, as has been done in China.

THE ECONOMICS OF GASIFIERS

For a technology to be economically viable, the capital cost of equipment as well as operating costs must be kept to an acceptable value. The open-top gasifier has been developed according to those criteria. An in-depth analysis by Reddy et al.

Table 3: Standards for treated industrial effluents in India

	Tolerance limits		
Feature	**into inland surface waters** *mg/liter*	**into irrigation lands** *mg/liter*	**into marine coastal areas** *mg/liter*
BOD	30	100	100
COD	250	–	250
Phenols	1	–	5

[21] indicates that decentralized power generation, such as can be obtained with renewable technologies, has a significant economic edge over conventional, centralized technologies.

In the present calculations, construction and installation times are considered to be negligible (less than six months) because the system is mostly made up of prefabricated items and site preparation is minimal. The payback period is determined by computing the extra costs incurred beyond those of a conventional diesel generator and the savings generated from the use of the new technology. Total operating costs include the initial capital outlay as well as subsequent running costs. Included under capital costs are equipment and construction costs (see table 4).

Costs are in dollars and Indian rupees (within parentheses) based on 1991 values. Values are nominal and based on actual numbers in most cases. The choice of 2,500 hours for the 4.4 kilowatt system is derived from the Hosahalli system, although an alternate scenario, which would raise the number of hours of operation per year to about 4,000, is also possible. Fixed costs, operating costs per kWh, and the total cost per kWh were obtained for diesel-only and dual-fuel modes, respectively. The total cost per year is the sum of fixed and operating costs; the total life of the project refers to the life of the building. Thus, replacement times for elements are based on the lifespan of the individual components. Present values are computed for all costs involved, with discount rates of 6 percent and 12 percent.

Maintenance costs

Maintenance costs for the diesel generator in both diesel-only and dual-fuel modes are the same, except for the cost of lubrication oil, which is higher in the dual-fuel mode. For 3.5 kilowatt systems in the dual-fuel mode, lubrication oil should be changed after every 250 hours of operation, as opposed to once every 500 hours in the diesel mode. For 100 kilowatt systems, the oil should be changed every 100 and 200 hours, respectively. From 3 to 6 percent of the total cost of a

Table 4: Cost parameters for 4.4 and 96 kilowatt systems[a]

P	Load	3.5 kW	80 kW
N	Number of hours per year	2,500	5,000
R	Diesel replacement	70 percent	70 percent
C_{eg}	Cost of engine gen-set	170 (34,000)	15,000 (300,000)
C_w	Cost of wood per tonne	5 (100)	15 (250)
C_{lub}	Cost of lubricating oil per liter	3 (60)	3 (60)
C_d	Cost of diesel per liter	0.28 (5.60)	0.28 (5.60)
C_{be}	Cost of building (diesel mode)	500 (10,000)	1,500 (30,000)
C_{bg}	Cost of building (dual-fuel mode)	750 (15,000)	5,000 (100,000)
C_g	Cost of reactor	150 (3,000)	1,000 (20,000)
C_k	Cost of cooling and cleaning system	225 (4,500)	7,500 (150,000)
C_{cs}	Cost of control system, if any	–	10,000 (200,000)
$L_{dg,r}$	Life of engine gen-set, reactor hours	25,000	25,000
$L_{cc,b}$	Life of cooling and cleaning system building, years	10, 40	10, 40
I_{dg}	Interest rate on all elements	12/6 percent	12/6 percent
S	Salvage value	10 percent	10 percent
m_{dg}	Maintenance of diesel gen-set	10 percent	10 percent
m_{gs}	Maintenance of gasifier system	5 percent	5 percent
m_b	Maintenance of building	5 percent	5 percent
S_{fc}	Specific fuel consumption diesel	280 g/kWh	280 g/kWh
S_{lc}	Specific lubricating oil consumption	1.36 g/kWh	1.36 g/kWh
T_c	Lubricating oil tank capacity	5 liters	5 liters
S_{wc}	Specific wood consumption	1.3 kg/kWh	1.3 kg/kWh
LC_{dg}	Labor cost in diesel mode	Rs2/hour	Rs2/hour
LC_{gs}	Labor cost in dual-fuel mode	Rs4/hour	Rs4/hour

a. The costs are in 1991 U.S. $ (1 $ = Rs 20) and Indian rupees (in parentheses).

system generally goes for maintenance, depending on the number of hours of operation [20].

Operating costs

Experience reveals that a gasifier engine–generator system in the dual-fuel mode can be operated by one skilled person and one semiskilled helper. Since operational costs do not increase during dual-fuel operation, the relative economics do not change. Any increase in operator costs, however, would lead to an increase in the cost of power. Consider, for example, a 3.7 kilowatt system run by two operators.

Table 5: Economics of diesel and dual-fuel modes at 6 percent interest rate[a]

Rated capacity *kilowatts*	**4.4**	**96**
	dual (diesel fuel)	dual (diesel fuel)
Load in kilowatts	3.5 (*3.5*)	80 (*80*)
Life of the plant in years	40 (*40*)	40 (*40*)
Capital cost per kilowatt engine gen-set + reactor	542.6 (*500*)	200 (*187.5*)
Present value of replacement of engine gen-set + reactor	566.51 (*522.15*)	514.35 (*232.2*)
Capital cost per kilowatt cooling, cleaning, and control system	64.3 (*0*)	218.75 (*0*)
Present value of replacement of cooling, cleaning, and control system	67.1 (*0*)	228 (*0*)
Total capital cost per kilowatt	**1,411.7 (*1,165*)**	**1,224.1 (*688.5*)**
Life cycle fuel cost per kilowatt	1,373.6 (*3,439.1*)	3,185.6 (*6,878.2*)
Life cycle operating and operating and maintenance cost per kilowatt	3,037.7 (*1,879*)	945 (*744.4*)
Fixed cost per kWh	0.033 (*0.0255*)	0.01905 (*0.00825*)
Operating cost per kWh	0.1275 (*0.152*)	0.0545 (*0.0735*)
Total cost per kWh	**0.1595 (*0.1775*)**	**0.0735 (*0.1135*)**

a. Italic figures denote the engine running on diesel alone. All cost figures are in U.S. dollars.

While use of a gasifier-based system raises the fixed costs of power generation considerably, reduced operating costs (made possible by the reduction in diesel fuel) more than offset fixed cost increases (see table 5). Indeed, the total cost of installation compares favorably with values quoted for coal-based thermal power generation systems because the economies of scale normally expected in megawatt-class power stations is obtained even at these power levels. The payback period depends both on the number of hours a system operates in a year, which is a key parameter, and the prevailing discount rates (see figure 13). If the number of hours of operation can be increased, the payback period will be lowered.

Larger systems (those with power outputs greater than 60 kilowatts), show a strong relation between payback, operating hours and the cost of wood chips (see figures 14 and 15). It is clear that as the interest rate increases from 6 to 12 per-

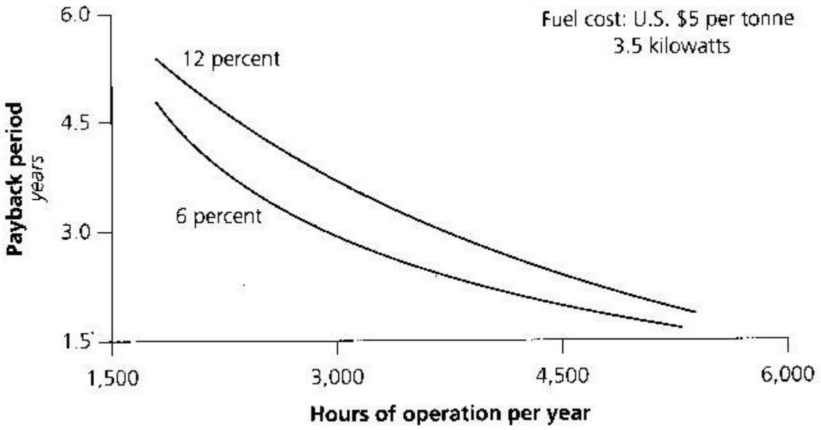


FIGURE 13: Payback period versus hours of annual operation for a 3.5 kilowatt gasifier system.

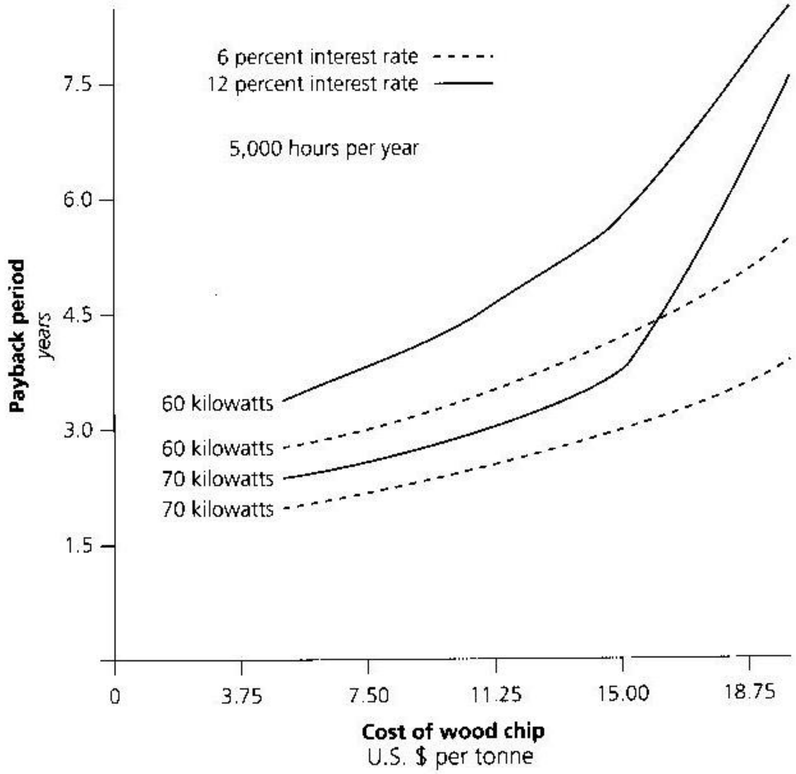


FIGURE 14: The variation of the payback period with the cost of wood chips for 5,000 hours of operation with 6 percent and 12 percent interest rates.

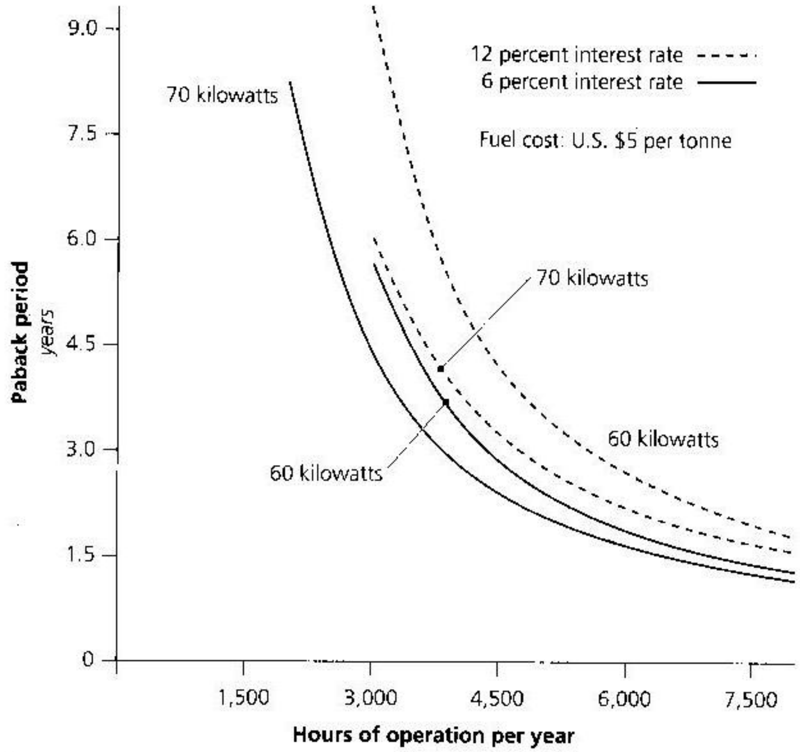


FIGURE 15: Payback period versus number of hours operated at 60 and 70 kilowatts power for a fuel cost of $5 per tonne of wood chips, at 6 and 12 percent interest rates.

cent, the payback period increases by 20 percent. Yet, increasing the number of operating hours, from 2,000 to 6,000 per year, reduces the payback period by a factor of about five. Although a fourfold increase in the cost of wood—from $5 (Rs 100) per tonne to $20 (Rs 400) per tonne—increases the payback period from 2.1 to 3.7 years, overall costs are affected much more by the number of operating hours than by the price of wood chips.

In 3.5 kilowatt systems, the difference in the cost per unit of electricity in diesel and dual-fuel mode is small, considering 2,500 hours of annual operating hours. Although operating costs are higher in the smaller system than they are in the larger systems, most of the extra cost can be attributed to the need for additional labor costs; trimming these costs would reduce the cost of unit electricity generated.

The value added to a system in the agricultural sector is very significant. Farmers in Karnataka benefited greatly from the 3.7 kilowatt water pumping system during the 1991 Persian Gulf crisis, during which diesel fuel was rationed. Thus, despite a doubling in labor costs, operating costs remained low. In addition, by doubling the operating hours from 2,500 to 5,000 per year, the payback period was reduced by about 40 percent. In such situations the economics of the 3.5 kilowatt system begins to match those of the larger system.

Results indicate that the cost of energy in the dual-fuel mode is substantially lower than in the diesel-only mode. The cost of energy provided by the state is around $0.065 (Rs 1.25) per kWh (which is generally subsidized). Thus the cost of energy from an engine–generator system in the dual-fuel mode is about 10 percent higher than what is charged by the state electricity board. The difference, however, is insignificant because the user is no longer dependent on the vagaries of a state-provided supply, especially when the value added to an industrial operation by the availability of energy is considerable.

CONCLUSIONS

Water pumping and electricity generation at various power levels are among the many applications that can be met with gasifier-based energy sources. Water-pumping demands are met more easily than the electric power demand because the load problems are less complex. But electricity can be supplied to an industry that has from 25 to 35 percent load variation by equipping a diesel engine in the dual-fuel mode with an "A" class governor, permitting strict control on frequency and load demands. Although no existing gasifier can generate more than a few hundred kilowatts of power, we see no particular difficulty in designing an efficient gasifier for megawatt power levels. The limiting factor, if one exists, will not be design-related but rather will be the availability of biomass, which must be harvested without undue environmental impact.

Economic considerations show that for the range of power levels now available, investing in gasifier-based power generation systems is a commercially attractive proposition, provided that the system is heavily used. Other beneficial aspects include the value of being able to install pumping or electricity generation systems in regions where the grid power supply is not reliable, which reduces investment in the system, lowering payback to a year or two for larger power systems. Thus, having looked at the system as a whole and subjected each element to scientific, technical, economic and aesthetic scrutiny, we see a bright future for the gasification technology around the world—if not immediately, then in the near future.

ACKNOWLEDGMENTS

The data presented in this chapter were obtained from wood gasifier projects administered and financed partly by the Karnataka State Council for Science and Technology in Bangalore and by the Department of Nonconventional Energy Sources in New Delhi. We thank them for their support. We would also like to thank the chapter's reviewers for their many useful comments. Finally, we are especially grateful to Amulya K.N. Reddy and P. Balachandra of the Indian Institute of Science for help with economic calculations.

WORKS CITED

1. Solar Energy Research Institute, Golden , Colorado, U.S. (SERI). 1979
Generator gas—the Swedish experience from 1939–1945.
2. Kaupp, A. and Goss, J.R. 1984
Small scale gas producer engine systems, German Appropriate Technology Exchange, Eschborn, Germany.
3. Coovattanachai, N., ed. 1986–1990
Rural Energy, RAPA Bulletin, especially pages 12–51, 1990/1, FAO Office, Bangkok.
4. Reed, T.B. and Markson, M. 1982
Biomass gasification reaction velocities, in R.P. Overend, T.A. Milne, and L.K. Mudge, eds., *Fundamentals of thermochemical biomass conversion,* 951–965, Elsevier Applied Science, New York.
5. Dasappa, S., Reddy, V., Shrinivasa, U., and Mukunda, H.S. 1985
Experience with gasifiers for 3.7 kW engines, *Ambio* 14:275–279.
6. Groeneveld, M.J. 1980
The co-current moving bed gasifier, Krips Repro Meppel, Twente University, Gröningen, the Netherlands.
7. Walawender, W.P., Chern, S.M., and Fan, L.T. 1985
Wood chip gasification in a commercial downdraft gasifier, in R.P. Overend, T.A. Milne, and L.K. Mudge, eds., *Fundamentals of thermochemical biomass conversion,* 911–922, Elsevier Applied Science, New York.
8. Huff, E.R. 1982
Effect of size, shape, density, moisture and furnace temperature on the burning times of wood pieces, in *Fundamentals of thermochemical biomass conversion: an international conference,* Solar Energy Research Institute, Golden, Colorado.
9. Mukunda, H.S., Paul, P.J., Shrinivasa, U., and Rajan, N.K.S. 1984
Combustion of wooden spheres—experiments and model analysis, presented at the twentieth symposium (international) on combustion, The Combustion Institute, 1619–1628.
10. Dasappa, S., Shrinivasa, U., Baliga, B.N., and Mukunda, H.S. 1989
Five-kilowatt wood gasifier technology: evolution and field experience, *Sadhana,* Indian Academy of Sciences proceedings in engineering sciences, 14:187–212.
11. Parikh, P.P., Bhave, A.G., Kapse, D.V., and Shashikantha 1989
Study of thermal and emission performance of small gasifier dual fuel engine system, *Journal of Biomass,* 19:75–97.
12. Ravindranath, N.H., Dattaprasad, H.L., and Somashekar, H.I. 1990
A rural energy system based on forest and wood gasifiers, *Current Science* 59:557–560.
13. Ravindranath, N.H., Dattaprasad, H.L., and Mukunda, H.S. 1989
Village electrification using wood gasifiers, *Proceedings of the first meeting on recent advances in biomass gasification technology,* Bombay, 211–229.
14. Dasappa, S., Shrinivasa, U., Dattaprasad, H.L., and Mukunda, H.S. 1989
Experience on running gasifier for village electrification, internal report, ASTRA, Indian Institute of Science, Bangalore.
15. Baliga, B.N., Dasappa, S., Shrinivasa, U., and Mukunda, H.S. 1991
Gasifier based power generation: technology and economics, to appear in *Sadhana,* Indian Academy of Sciences proceedings in engineering sciences.
16. Bokalders, V. and Kjellstrom, B., eds. 1990
Renewable energy for development, a Stockholm environment institute newsletter, 4:1–24.

17. Graf, U. 1990
Small charcoal gasifiers in projects of technical cooperation, reports 1–3, University of Bremen, Bremen, Germany.

18. Kaupp, A. 1984
Gasification of rice hulls: theory and praxis, German Appropriate Technology Exchange, Eschborn, Germany.

19. Kardona, 1988
The potential of biomass gasifier generator sets as an alternative power plant for rural electrification in Indonesia, Proceedings of the International Conference on Energy from Biomass and Wastes XII, New Orleans, Louisiana, Institute of Gas Technology, Chicago, U.S.

20. Zerbin, W.O. 1984
Generating electricity by gasification of biomass, in A.V. Bridgwater., ed., *Thermochemical processing of biomass*, Butterworths, London.

21. Reddy, A.K.N., Sumithra, G.D., Balachandra, P., and D' Sa, A. 1990
The comparative costs of energy conservation and generation from decentralized and centralized sources, *Economic and Political Weekly*, 2 June, 1201–1216.

17
ADVANCED GASIFICATION-BASED BIOMASS POWER GENERATION

ROBERT H. WILLIAMS
ERIC D. LARSON

A promising strategy for modernizing bioenergy is the production of electricity or the cogeneration of electricity and heat using gasified biomass with advanced conversion technologies.

Major advances that have been made in coal gasification technology, to marry the gas turbine to coal, are readily adaptable to biomass applications. Integrating biomass gasifiers with aeroderivative gas turbines in particular makes it possible to achieve high efficiencies and low unit capital costs at the modest scales required for bioenergy systems. Electricity produced with biomass-integrated gasifier/gas turbine (BIG/GT) power systems not only offers major environmental benefits but also would be competitive with electricity produced from fossil fuels and nuclear energy under a wide range of circumstances. Initial applications will be with biomass residues generated in the sugarcane, pulp and paper, and other agro- and forest-product industries. Eventually, biomass grown for energy purposes on dedicated energy farms will also be used to fuel these gas turbine systems.

Continuing improvements in jet engine and biomass gasification technologies will lead to further gains in the performance of BIG/GT systems over the next couple of decades. Fuel cells operated on gasified biomass offer the promise of even higher performance levels in the period beyond the turn of the century.

INTRODUCTION

Power generation is a route to the modernization of biomass for energy offering opportunities for substantial industrial development before the turn of the century. Already in the United States, installed biomass-electric generating capacity is of the order of 9,000 megawatts-electric (MW_e) [1] (see table 1). Much of this capacity was installed as a result of incentives provided by the Public Utility Regulatory Policies Act of 1978 (PURPA), which requires a utility to purchase electricity from cogenerators and other qualifying independent power producers at a price equal to the utility's avoided cost. There is not yet much biomass power generating capacity in the rest of the world, where PURPA-type incentives have not been available.