Energy for Sustainable Development 15 (2011) 231–239

Contents lists available at ScienceDirect

Energy for Sustainable Development

Operational experience on a grid connected 100 kWe biomass gasification power plant in Karnataka, India

S. Dasappa [a,*], D.N. Subbukrishna [b], K.C. Suresh [b], P.J. Paul [b], G.S. Prabhu [c]

[a] Centre for Sustainable Technologies, Indian Institute of Science Bangalore, India
[b] Combustion Gasification and Propulsion Laboratory, Dept of Aerospace Engineering, Indian Institute of Science Bangalore, India
[c] Biomass Energy for Rural India, Indian Institute of Science Bangalore, India

ARTICLE INFO

Article history:
Received 26 November 2010
Revised 19 March 2011
Accepted 19 March 2011
Available online 13 April 2011

Keywords:
Distributed power generation
Grid connection
Biomass gasification system
Rural energy

ABSTRACT

The paper reports the operational experience from a 100 kWe gasification power plant connected to the grid in Karnataka. Biomass Energy for Rural India (BERI) is a program that implemented gasification based power generation with an installed capacity of 0.88 MWe distributed over three locations to meet the electrical energy needs in the district of Tumkur. The operation of one 100 kWe power plant was found unsatisfactory and not meeting the designed performance. The Indian Institute of Science, Bangalore, the technology developer, took the initiative to ensure the system operation, capacity building and prove the designed performance.

The power plant connected to the grid consists of the IISc gasification system which includes reactor, cooling, cleaning system, fuel drier and water treatment system to meet the producer gas quality for an engine. The producer gas is used as a fuel in Cummins India Limited, GTA 855 G model, turbo charged engine and the power output is connected to the grid.

The system has operated for over 1000 continuous hours, with only about 70 h of grid outages. The total biomass consumption for 1035 h of operation was 111 t at an average of 107 kg/h. Total energy generated was 80.6 MWh reducing over 100 t of CO_2 emissions. The overall specific fuel consumption was about 1.36 kg/kWh, amounting to an overall efficiency from biomass to electricity of about 18%. The present operations indicate that a maintenance schedule for the plant can be at the end of 1000 h. The results for another 1000 h of operation by the local team are also presented.

Introduction

As a part of Global Environment Facility (GEF) program with partners from the United Nations Development Programme (UNDP) and Ministry of New and Renewable Energy (MNRE), the Government of Karnataka undertook the responsibility of implementing the project — Biomass Energy for Rural India (BERI). The BERI project is intended to demonstrate the use of decentralized renewable energy production technology to augment rural energy access, availability and capacity building of local communities to manage energy systems in a sustainable way.

The project is aimed at developing and implementing a bio-energy technology package to reduce Green House Gas (GHG) emissions and to promote a sustainable and participatory approach in meeting rural energy needs. The project is being implemented in five village clusters (or *taluks*) with a total of 26 villages in the state of Karnataka, India (BERI, 2010). The five clusters were from different taluks: Koretegere, Madhugiri, Sira, Tumkur, and Gubbi.

The major focus of the project was to address,

- Development objective:
  To reduce carbon dioxide emissions through promotion of bio-energy as a viable and sustainable option to meet the rural energy service needs in India.
- Immediate objectives:
  - To develop and demonstrate a decentralized bio-energy technology package for providing quality rural energy services for lighting, pumping drinking water, cooking, pumping irrigation water and agro-processing (e.g., flour mill).
  - To develop technical, institutional and financial mechanisms to overcome barriers for large scale adoption and commercialization of bio-energy technology packages.

The technology related objectives are:

- Demonstration of technical feasibility of biomass gasification technology on a significant scale in a rural environment;
- Capacity building using local persons power for training and plant operation and development of appropriate mechanisms for implementation, management and monitoring of the project;

* Corresponding author.
E-mail address: dasappa@cgpl.iisc.ernet.in (S. Dasappa).

0973-0826/$ – see front matter © 2011 International Energy Initiative. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.esd.2011.03.004

- Developing financial, institutional and market strategies to overcome the identified barriers for large scale replication of the biomass technology package for decentralized applications; and,
- Dissemination of the biomass gasification technology and information package on a large scale of the bio-energy technology and information package.

The project is expected to bring significant socio-economic and environmental benefits both at local and global level. As a part of this program, gasification technology was chosen towards meeting part of power requirements of five village clusters, using local resources, like forest residues and biomass from an energy plantation. It must be brought out that the project envisaged locating distributed power generation system using gasification technology at small power level over the entire project area. The initially envisaged activity was to have distributed small power capacity gasification systems of about 20–50 kW capacity to meet the illumination, drinking and irrigation water electricity demand at individual village level. Based on the prevailing conditions in the project area at the time of implementation of this project, like the load profiles and the demand for electricity, the management group in BERI opted to have the grid connected power projects with an option to supply electricity to critical loads in the community in islanded mode in an event with grid failure.

Background information

Ministry of Power (MoP), Government of India (MoP, 2010) estimates about 8% of power deficit is prevalent in the country. This has strained the availability of power in rural areas. On the rural electrification front, the Ministry estimates that 74% of villages are electrified with still 154,230 villages remaining un-electrified. Of these around 18,000 villages have difficulty in linking with the grid and hence should be electrified by a decentralized source of energy. Even in the so called grid linked villages the quality and availability of power is poor. In order to mitigate this power shortage, MoP has launched an ambitious program called "Power for all" by 2012. The underlying approach of this program is to strengthen power generation in the country by utilizing locally available resources in a sustainable manner. This has paved way for MNRE to launch other missions like the Jawaharlal Nehru National Solar Mission aimed at creating an enabling policy framework for the deployment of 20,000 MW of solar power by 2022 to support the energy demand. Another in-built important benefit in establishing decentralized power generation is the reduction of transmission and distribution losses. Further, any addition of power into a tail end grid (decentralized generation) helps in stabilizing the grid voltage and frequency apart from reducing losses. Kumar et al. (2008) have carried out simple analysis of a rural grid where the performance of a 4 MW rural feeder was very poor; the voltage level at all the busses was found to be less than 0.86 pu (per unit = voltage/nominal voltage) and also at few busses it was as low as 0.69 pu. The total feeder losses were high, equal to 1.44 MW which was about 29.4% of the power supplied to the feeder. Using decentralized power generation and feeding into the grid shows remarkable improvement in the performance of the feeder with all the bus voltages reaching the acceptable limits from very low values. The system real power losses fell from 29.4% to only about 4.7% of the power supplied to the feeder. Some of the above studies further encourage the need for distributed power generation systems.

There is a realization of the need to search for decentralized and renewable energy based options to meet rural energy needs in a sustainable way (Reddy, 1999; Ravindranath et al., 2000). Among the renewables, bioenergy technologies are also being explored for meeting rural electricity needs by the Ministry of New and Renewable Energy sources. One such technology is biomass gasification which efficiently uses locally available bio-resources such as forest residues, agricultural residues, etc. and converts them into a clean gas that can be utilized in dual-fuel or gas engines for power generation. It must be emphasized that the choice of technology package for distributed power generation is an important aspect. The conventional use of biomass for power generation has been the combustion/steam route, which is reasonably efficient and economical in the power range of 5 MW and above. The typical conversion efficiency from biomass to electricity is about 20% at the 5 MW level. Gasification offers a better solution in addressing power generation using biomass at small and medium power ranges with overall efficiency in the range of 20% at 100 kW to about 30% at a MW level. This distributed power generation system can compete with the combustion route modules of 2 MW electricity, considering overall plant efficiency (Dasappa, 2010).

A major activity was carried out at the Indian Institute of Science towards meeting the unmet demand of electricity in the year 1988 at Hosahalli (Srinivas et al., 1992; Somashekar et al., 2000; Ravindranath et al., 2004). Hosahalli, previously an un-electrified village, was probably the first village to be served by a biomass gasifier in terms of quality supply of electricity. The village is located 100 km from Bangalore in Tumkur District, Karnataka. It has about 45 houses with agriculture being the main occupation of the people. Kerosene was used in traditional wick lamps for lighting. Women carried water from a polluted open water tank nearly 1 km away from the village. Farmers depended on rainfed agriculture, and were subject to the vagaries of monsoon and low crop yields. The 3.75 kWe capacity biomass gasification system coupled to a diesel engine installed in the year 1988 was providing electricity for domestic illumination, street lighting and piped drinking water supply. The capacity was enhanced to 20 kWe in 1997 with addition of other services like, flour milling and irrigation water requirements as well. The total connected load comprising of 4 tube wells, domestic lighting for 45 houses, street lights and a flour mill was about 32 kW. The system package used a dual-fuel engine, i.e., using gas and diesel.

Summarizing the plant performance for a 5-year time period between 1998 and 2003, the availability of power generation system was in excess of 90%, except during the year 2000 due to major maintenance in the gasification and engine system (Ravindranath et al., 2004). Of this 90% availability, the dual-fuel mode supported by biomass gasifier unit was operational for over 70% of the time. The load stabilization also improved the diesel substitution to as high as 87%. The fuel consumption was about 1.28 kg wood and 65 mL of diesel per kWh.

Thus, the basic services critical for determining the quality of life such as home, street lighting, piped water supply for drinking and irrigation were provided over 85% of the days (1998–2004) a unique achievement for a village in India compared with the centralized facility. Lack of co-operation from the village to manage the project arising from the fact that the basic infrastructure support, like electricity, water, etc., should be provided by government, along with some groups with vested interest within the village to get the state grid electricity closed the project in the year 2006. However, even after grid connection, the supply was unable to ensure the same quality of power that was available through the gasifier based power system due to frequent power outages — a feature existing in most of the rural grids. Further, the gasifier based project was addressing services like water, illumination, etc. and not merely electricity.

Ghosh et al. (2004) highlight the use of biomass gasification plant using dual-fuel engines for Gosaba Islands of Sundarbans with a population of 10,000 in five villages. Five 100 kWe diesel engines, each coupled to gasifier systems, are used to generate electricity. Electricity is provided to majority of the population, both for domestic and industrial applications. The average fuel consumption works out to be about 0.82 kg/kWh of wood and 135 mL/kWh of diesel, which accounts for about 60% diesel replacement or saves about 60% of the diesel compared with operating the engine with only diesel as the fuel.

Hammond and Kemausuor (2008) summarize the experience of using gasifiers in Africa. In Uganda a 10 kWe system was supplied by an Indian company, Ankur Scientific Energy Technology Pvt. Limited, to operate on dual-fuel mode. A minigrid was connected to a farm house, pig sty and security lights. Eucalyptus branches are used as fuel, with a generation of about 18 kWh daily with a specific fuel consumption of 0.84 kg of wood/kWh and 0.17 liters of diesel per kWh. A simple analysis of the data indicates a diesel substitution of about 60%.

Gasification system — a brief

A typical gasifier system configuration is shown in Fig. 1. The open-top downdraft reactor design is made of a ceramic lined cylindrical vessel for improved life in the highly corrosive thermal environment inside the reactor, along with a bottom screw for ash extraction. In brief the reactor has air nozzles and open top for air to be drawn into the system to help in improving the residence time of the gas and enabling cracking of higher molecular weight compounds. The novelty in the design arises from the dual air entry – air being drawn from the top of the reactor and also through the nozzles – which permits establishing a flame front moving towards the top of the reactor, thus ensuring a large thermal bed inside the reactor, to improve the gas residence time. The details of the gasification technology are discussed in Dasappa et al. (2004). A unique screw-based ash extraction system allows for extracting the residue at a predetermined rate. The gas is cooled and cleaned by direct contact with water sprays in the cooler and scrubber. During this process water is contaminated with both dust and some organic compounds like phenols, aldehydes, etc., which is treated in a water treatment plant. The total gas conditioning system involves cyclone, scrubbers and fabric filter. The gas is then de-humidified or dried using the principle of condensate nucleation, to reduce the moisture and fine contaminants. A blower provides necessary suction for meeting the engine requirements.

Water used for cooling and cleaning the gas is pumped at the required flow rate into the cooler and the scrubber where the gas gets cooled and cleaned. A separate water circuit is provided for the dehumidifying scrubber with low temperature water. Details of the water treatment process are discussed later. Fig. 2 shows the water circuit in the gasification system.

The BERI project details

The project has six gasifier based power plants comprised of two 100 kWe and one 200 kWe in Kabbigere and one each of 240 kWe capacity in Borigunte and Sebinayanapalya. The total installed capacity of all the plants is 880 kWe. While the systems were undergoing performance guaranteed operations at Kabbigere, by the two selected manufacturers after due tendering process, one of the 100 kWe systems, after preliminary testing, was handed over to the local community for operations with limited training. The local community along with support from BERI operated the power plant for about 900 h. There were many operational issues which were thwarting continuous system operation. These were related to power output decreasing with time, blockages of piping, filters, etc. and finally break down of the system sub elements, like coolers, reactor, water treatment, etc.

At the request of BERI project management, Indian Institute of Science, (IISc) the technology developer for all the gasifiers deployed in the project area, reviewed the 100 kW gasification system in detail. The investigations revealed that improper operational procedures had seriously affected the hardware. These were related to usage of moist fuel and improper maintenance practices. The water used in gas cooling and cleaning was recirculated without any treatment, resulting in excessive contamination of the water which also affects the quality of gas. There were also issues related to grid tripping.

The objectives of IISc's involvement at this stage were to

- operationalize the 100 kW power plant in co-ordination with the BERI team for continuous electricity generation and performance evaluation.
- train the local manpower for systematic and continuous plant operation.

Owing to reasons stated earlier, the performance of the 100 kWe system at BERI was far from the already accomplished and documented results (Dasappa et al., 2005; Sridhar et al., 2005a,b). Based on the request from BERI, Indian Institute of Science took the initiative towards establishing the performance of the 100 kW system at the project site. The areas that were addressed, related to maintenance of the brick lining similar to any furnace, replacing the damaged filters and enabling the water treatment plant. The ash extraction system was upgraded to ensure convenience and reduce the effort for removing the ash. This paper highlights the performance of the system during the 1000 h of operation, specific to biomass consumption, load, gas composition, emissions and related aspects.

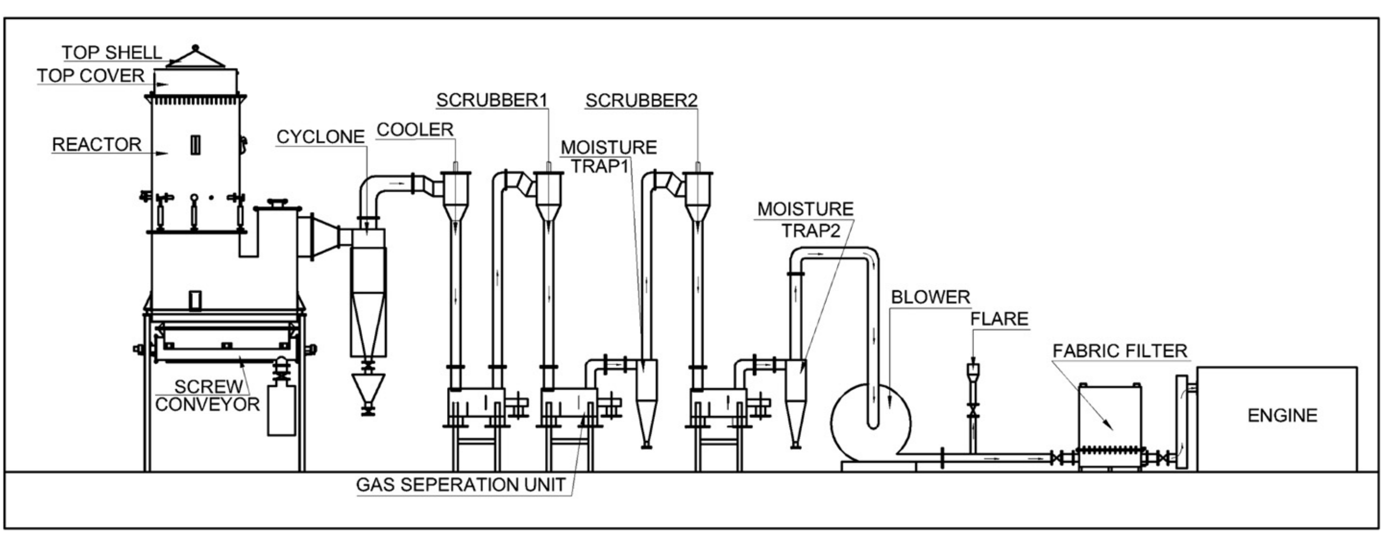

Fig. 1. Schematic of the biomass gasification plant.

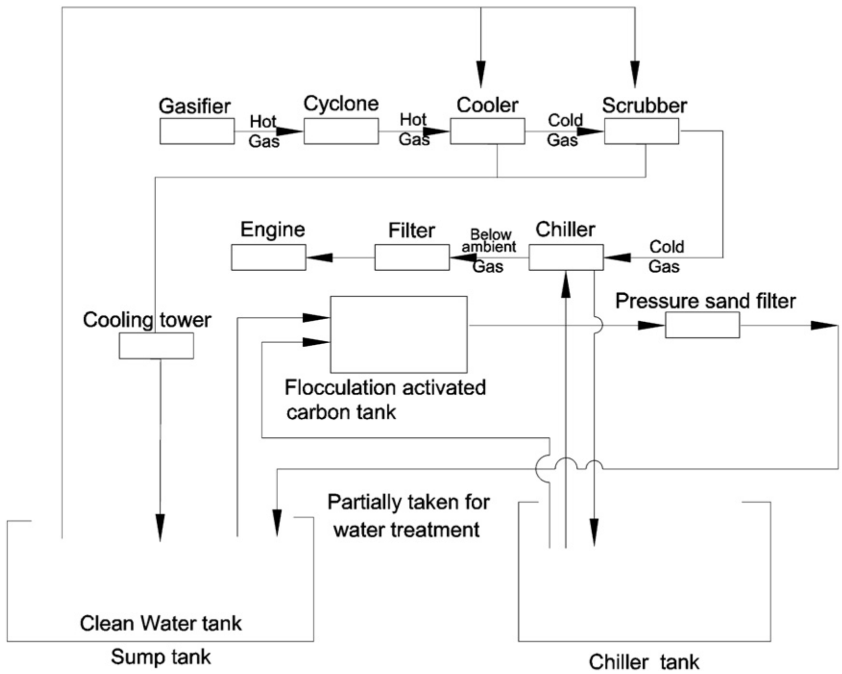

Fig. 2. Schematic of the water circuit in the gasification plant.

Overall plant configuration

The gasification system consists of an IISc open top dual air entry reactor, cooling and cleaning system and a char removal system. The producer gas from the gasification system was designed to feed a turbocharged after cooled producer gas engine with nominal rating of 120 kWe. The power generation system is a Cummins India Limited make producer gas engine which has six cylinders with spark ignition system along with an electronic governor, turbo charger and an after cooler. The gasification system specification of the open top down draft reactor was to gasify about 135 kg/h of biomass amounting to about 350 kg/h of producer gas to fuel the producer gas engine. Fig. 1 provides the schematic of gasification system elements.

A drier using diluted engine exhaust gasses conditioned the biomass to moisture level less than 12% as required by the gasification system. Dry biomass from the dryer is fed using an electrical hoist and biomass bin. The engine is fitted with indigenously designed producer gas carburetor for maintaining the air-to-fuel ratio over the range of loads. Power generated was exported to 11 kV grid with all the safety systems and a step up transformer. The detail specifications are in Table 1.

Fuel source and preparation

The gasification system capable of operating on a range of biomass, including biomass briquettes, was operated using woody biomass. Biomass used for the gasification was sourced from the project-supported dedicated multi species plantation. Fuel was sized using a multi-blade cutter in the range from 25×25×25 mm to about 50×50×50 mm depending on the feed stock. Table 2 provides fuel characteristics used in the gasifier. The fuel was loaded to a batch drier using diluted engine exhaust for drying the fuel. Typical residence time of the wood was in the range of 2–4 h depending upon the initial moisture content in the fuel. Fuel from the drier was loaded to the gasifier using a conveyor depending upon the fuel consumption.

Table 1
Specifications of the producer gas engine.

Parameter	Specifications
Make and model	Cummins India Limited, GTA-855-G
Engine type	In-line, 6 cylinder, 4-stroke, turbo-charged with after cooler gas engine, spark ignited
Bore (mm)	140
Stroke (mm)	152
Total displacement, liters	14
Compression ratio (CR)	8.5
Rating @ 1500 rpm	120 kWe with producer gas

Gasifier performance

The gasification system was initially tested for establishing the performance in the blower mode. Gas was generated and flared at the burner towards ensuring all the process parameters, like pressure drop across various system elements, fuel loading, ash extraction, gas cooling, water quality and the gas quality is as per the design. It was found the gasification system can be operated at the rated condition of 135 kg/h continuously. After establishing the gasifier performance, engine was operated in the grid connected mode. During this period, all the relevant parameters indicated above along with the electrical parameters, like voltage, current and frequency, were recorded. The following sections will highlight the operational performance of the total package.

Pressure drop across reactor

This is an important parameter related to the operation of the gasification system. The reactor pressure drop provides information related to the packed bed dynamics occurring inside the reactor

Table 2
Fuel properties.

Parameter	Description
Size	25 mm to 50 mm in diameter and length
Moisture	10–15%
Ash	~3–5%
Density	550–650 kg/m^3
Bulk density	350–400 kg/m^3

where thermo-chemical conversion processes take place. As can be seen from Fig. 3, the resistance posed by the bed for the gas flow is about 1500 ± 500 Pa. Other derived information from the data is regarding the capability of the reactor to continuously produce gas without building up the resistance that could result in reducing the gas flow rate and the electrical load, a critical issue of any fixed bed system. This parameter decides the overall health of the system. At the rated condition the gas mass flux is about 0.22 kg/m^{2}s. Under these conditions, the propagation rate within the fixed bed is sufficient to establish the thermal profile above the air nozzles to provide adequate residence time both for the solid and the gaseous species to ensure conversion processes are nearly complete (Dasappa et al., 2004).

Fig. 4 highlights the biomass consumed during the one thousand hours of operation. Based on this data, the average consumption rate has been in the range of 110 ± 10 kg/h, and the residue removal is about 5 ± 0.5 kg/h. The residue extracted depends on the ash content in the biomass, and in the present case is about 3.5–4.5%.

Gas quality

Gas composition was measured using SICK Maihak online gas analyzer. CO, H_2, CH_4, CO_2 and O_2 were recorded on a data acquisition system for certain duration during 1000 h of operation. Tar and particulate in the gas was measured using wet method (Mukunda et al., 1994). The gas composition measurement was restricted to part of the duration due to the portability of the equipment between the laboratory and the project site. A typical gas composition trace is presented in Fig. 5. The gas composition was measured over a period of about five hours during the plant operation. Measured compositions show CO and H_2 in the range of 18 ± 1%, CH_4 1.8 ± 0.4%, CO_2 9 ± 1% and the rest N_2. The composition would result in a gas calorific value of about 4.5 ± 0.3 MJ/kg.

The tar and particulate emission measurements were conducted at the exit of the gas filter using methoxy-benzene as the solvent. The results from four tests showed that the average particulate content in the gas was in the range of 19 ± 2 mg/m^3 of gas while the tar was in range of 10 ± 2 mg/m^3.

Water treatment and quality

Water quality was measured as per the standards of the Pollution Control Board for liquid discharge. Biomass moisture content was recorded using a pre-calibrated capacitance based meter. Fig. 6 provides the block diagram of the water treatment scheme used in the plant. Water treatment was carried out on all days during the gasifier plant operation. About 50 m^3/h of water is circulated through the gas cooling and cleaning system of the gasifier plant continuously which picks up particulate and condensable matter from the gas. This increases the concentration of particulate and other condensable mater in the circulated water. To keep the water quality good for recirculation an average of about 20 m^3 of water was treated daily. Four batches of treatments are done daily on a regular basis. Water for treatment is first pumped to the flocculation tank, is then treated with activated carbon, alum and polyelectrolyte and filtered through sand bed filter. The clear water free of particulate, color and odor is taken back to the sump for recirculation. A cooling tower is used to reduce the water temperature. The same water was circulated throughout the 1000 h of plant operation with occasional makeup for losses due to evaporation amounting to about 1 m^3 daily. Detailed water analysis was done after about 1000 h of plant operation.

Engine and generator performance

Biomass consumption was logged by monitoring each charge being loaded and similarly the char removed at regular intervals was weighed using a balance. Electricity generated was measured using a kWh meter on the control panel and cross checked with the voltage and ammeter recordings. The power factor was found to be around 0.92.

Fig. 7 depicts the electricity generated by the producer gas engine generator during the 1000 h of operation. From Fig. 7 it is clear that the average load on the engine is in the range of 85 ± 6 kWe. The electricity generated was exported to the grid. It is important to recognize that the entire power package has been able to generate nearly constant load. Some of the lower loads recorded are due to the grid failure and reloading the system. During the grid failure the entire system was operated on the internal load without stopping either the engine or the gasification system. There were about 10 grid failures during this operation, amounting to about 70 h of in-house load operation without exporting electricity to the grid. The engine exhaust emissions were measured using Quintox make online analyzer. The averages of several readings are CO is 10,410 mg/m^3 and NO_X is 126 mg/m^3. The guidelines for emissions from biomass gasification plant for gas engine applications (Anon, 2009) suggest standards used in Denmark and Germany. Denmark uses 3000 mg/m^3 and 550 mg/m^3 respectively for CO and NOx at 5% exhaust oxygen in the exhaust, whereas in Germany, the limit values are 650 mg/m^3 for CO and 500 mg/m^3 for NOx. Comparing with the present measurement,

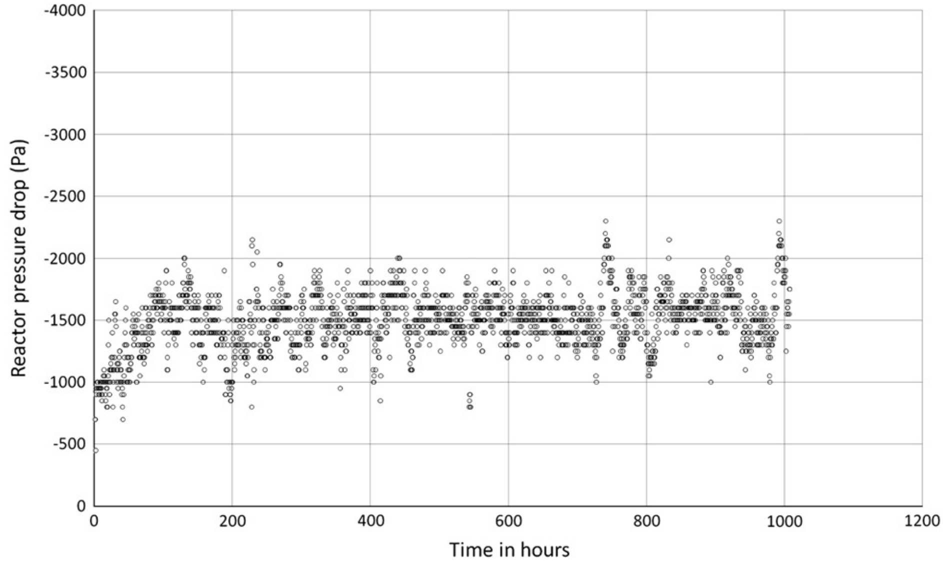

Fig. 3. Reactor pressure drop at the rated condition of the gasifier system.

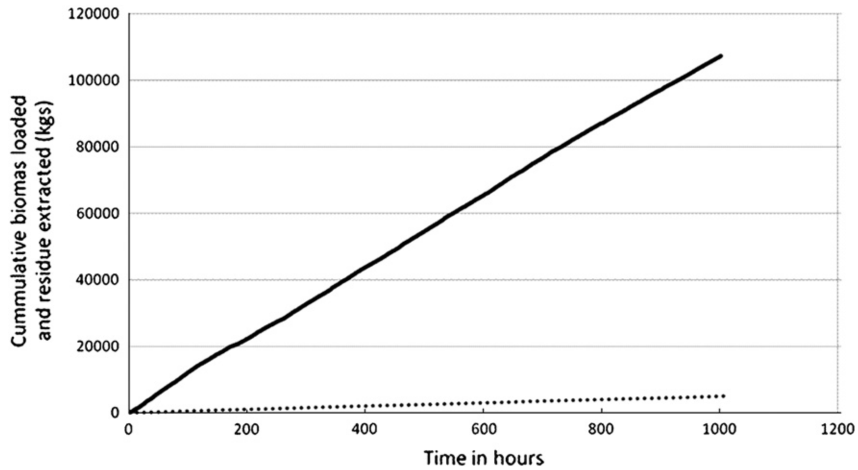

Fig. 4. Biomass loading and residue extraction with time for the 1000 h of operation. Full line — biomass consumption; Dotted line — ash extraction.

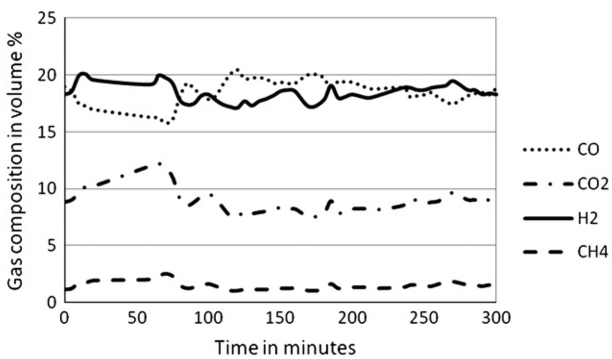

Fig. 5. Producer gas composition at a load of 90 kWe.

CO level is slightly higher compared with the German standard, reflecting on the in-cylinder combustion process with producer gas as fuel having incomplete combustion with CO. A catalytic converter may probably be required at the engine exhaust to meet the emission standard. In the present case, the engine exhaust gas is diluted with air to reduce the temperature from nearly 750 K to about 375 K for drying the moist wood chips thus the concentration of CO and NOx would be lower by about 20%.

Overall performance

In summary the engine was operated for 1022 h with a grid synchronized run of 951 h. The total biomass consumption for 1035 h of operation is 111 t at an of average 107 kg/h consumption. The total energy generated is 80.6 MWh and the net energy exported to the grid is 56.5 MWh.

Specific fuel consumption

The specific biomass consumption for the entire 1000 h of operation is about 1.36 kg/kWh of gross electricity generation. This is slightly higher than the average specific fuel consumption recorded on similar engines at 1.2 kg/kWh (Sridhar et al., 2005a,b) using wood chips. The plant has operated at an average load of about 85 kWe, with peaking at around 100 kWe. The present average load is around 85 kWe, and the rated capacity of this engine is 120 kWe, probably accounts for some of the inefficiencies. The reason for slightly lower average load needs further investigation. The other reasons for higher SFC are related to the ash content of the fuel, which about 3.5% is compared with the earlier reported work (Sridhar et al., 2005a,b) of less than 1.0% and also the grid failures, during which the plant is operated at lower loads.

With specific fuel consumption at 1.36 kg/kWh and the measured calorific value of biomass used at 15 MJ/kg, the overall efficiency of conversion of biomass to electricity is about 18%. Based on the gas composition and the derived calorific value, cold gas efficiency, defined, as the ratio of energy in biomass to the energy in the producer gas is 77%, consistent with the detailed measure carried out in the laboratory (Mukunda et al., 1994). Further the engine efficiency defined as the ratio energy in the gas to electricity generated works out to be 25%, lower by about 6 points compared with natural gas operation. The main reasons for the reduction in efficiency are related to the higher exhaust temperatures, properties of producer gas and also combustion processes with producer gas inside the engine cylinder. It is evident from the CO measurements that some energy is lost amounting to about 6% of the

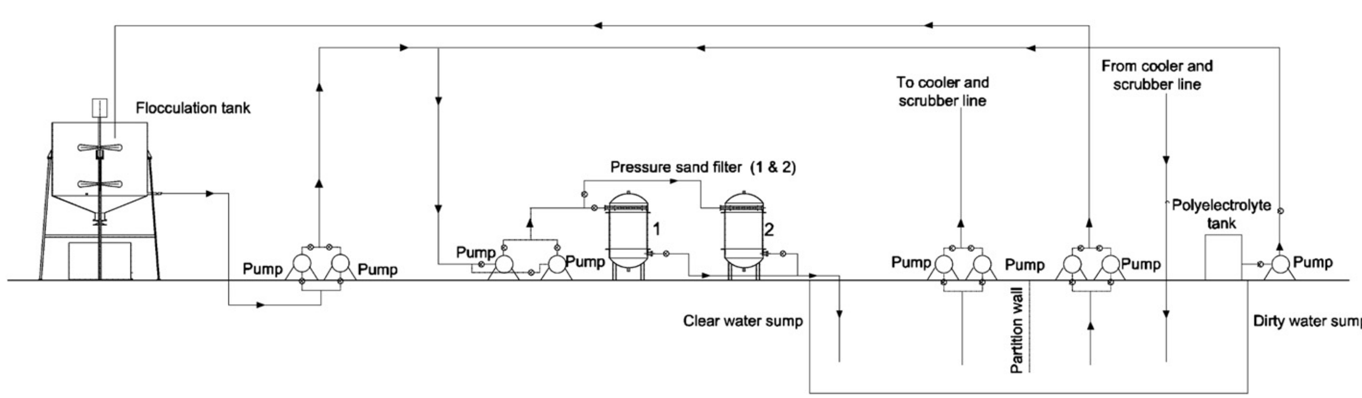

Fig. 6. Block diagram of the water treatment process.

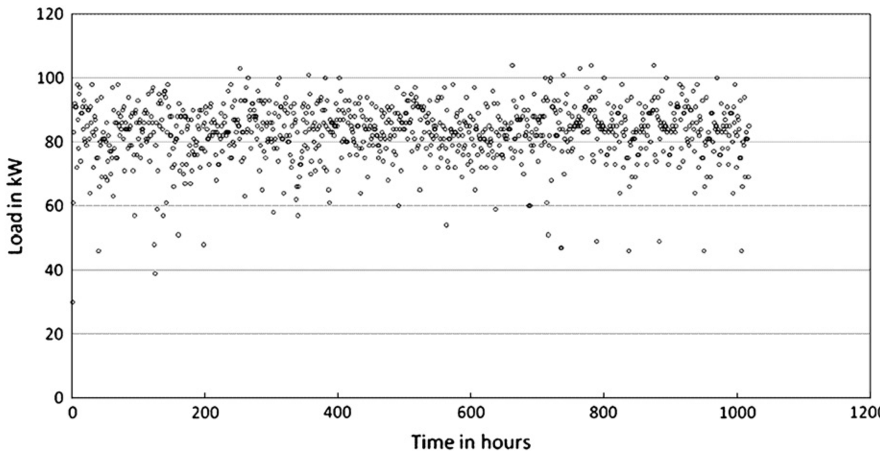

Fig. 7. Electricity generated during the 1000 h of operation.

energy input into the engine. These aspects have an effect on the engine efficiency. Detailed analysis towards this has been carried out by Dasappa (2001) and Sridhar et al. (2005a,b).

It is important to recognize that even at 100 kWe the conversion efficiency from biomass to electricity in a gasifier engine system is around $18 \pm 1.5\%$, compared with a 100 MWe coal based power plant at 34% (CEA, 2006). At larger capacities, of about 500 kWe the efficiency is in the range of 25 to 30% (Dasappa et al., 2005; Sridhar et al., 2005a,b).

Water quality

Measurements on the quality of water used for cooling and cleaning the producer gas are presented in Table 3. The data comprises of the blank water (from the tube well used as a source of water), untreated water and treated water. Water from the sump tank represents the water in the total circuit and the treated water represents the discharge from the treatment plant to the sump as shown in Fig. 6 for circulating water. The data regarding the limits refer to the permissible pollution limits set by the Karnataka State Pollution Control Board (KSPCB, 1986) for inland discharge. There has been no odor from the gasification plant, a clear indication of treatment being operating satisfactorily.

As can be seen from the data, it is clear that except for total dissolved solids (TDS), Kjeldahl Nitrogen and Ammoniacal nitrogen with all other parameters are well within the limits. It must be highlighted that this water is for circulation and not for discharge. The water for discharge was specifically treated and found that even the above mentioned parameters meet the emission standards as per the discharge norms.

Training and maintenance

The other objective of capacity building has been found successful. Three supervisors and 6 operators were trained during this period. All the do's and don'ts have been explained and at the time of writing this paper, the plant has operated for over 1000 h by the local team at an average load of about 90 kW, with all the operating parameters under control.

The filter cartridge used for gas filtration requires maintenance at an average of about 40 h of operation. There are two parallel filters, thus ensuring continuous operation of the plant during the filter maintenance. The other components can be maintained at the end of 1000 h. A new filter device has been developed with a facility for online cleaning thus eliminating the laborious manual cleaning of filter cartridges. This is implemented at the project site. The engine oil has to be changed at intervals as recommended by the manufacturer.

The gas quality measured using wet method revealed very low contamination (Section Gas quality). This was further confirmed when the critical engine components of the engine were examined at the end of 600 h of operation. The gas control valve, turbo compressor and the after cooler had no deposits, suggesting that the gas was clean enough.

Fig. 8 shows the performance of the system for 95 days amounting to about 2000 h of operation. After about 40 days of successful operation, the local team has taken the responsibility of operating the power plant. It is clear from Fig. 8 the first 1000 h was nearly continuous and was completed in about 40 days. The subsequent 1000 h has been completed in about 55 days. It can be seen from Fig. 8 that over 75% of the days the plant has operation for nearly 24 h. The other outages are due to some grid disturbance and maintenance. Further some of the shortfall in the operational hours is related to

Table 3
Blank and treated water sample analysis report (sample drawn after 1000 h of continuous run).

Tests	Limits MAX as per KSPCB	Fresh water (blank sample)	Sump water	Treated-unfiltered
Color and description		Colorless	Pale gray	Colorless
PH	6.0–9.0	7.08	8.49	7.98
Total chlorides, Cl, mg/L	1000	11.2	259	240.6
Total dissolved solids, mg/L	2100	246	1276	2574
Total suspended solids, mg/L	100	2	60	4
COD, mg/L	250	7.9	222	24.7
BOD, mg/L	30	1.2	13.5	6.3
Total Kjeldal nitrogen, as N, mg/L	100	1.7	552.1	637.6
Ammoniacal nitrogen, as N, mg/L	50	<0.5	474.2	425
Free ammonia as NH_3, mg/L	5	<0.05	72.3	7.5
Oil and grease, mg/L	10	<1	<1.0	<1.0
Conductivity in micro ohms/cm	2250	362	5040	4640
Cyanide as CN, mg/L	0.2	Absent	Absent	Absent
Total sulfates, as SO_4, mg/L	1000	6.2	304.8	711.5
Zinc as Zn, mg/L	5	0.03	0.06	0.03
Copper as Cu, mg/L	3	<0.05	<0.05	<0.05
Lead as Pb, mg/L	0.1	<0.01	<0.01	<0.01
Total chromium, as Cr, mg/L	2	<0.01	<0.01	<0.01
Hexa valent chromium as $Cr6^{+}$, mg/L	0.1	<0.01	<0.01	<0.01
Mercury as Hg, mg/L	0.01	<0.001	<0.001	<0.001
Nickel, as Ni, mg/L	3	<0.01	<0.01	<0.01
Total residual chlorine, mg/L	1	<0.05	<0.05	0.03
Phenolic compound as C_6H_5OH, mg/L		Absent	Absent	Absent

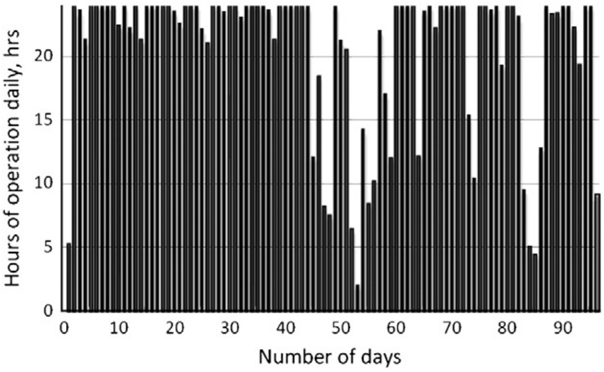

Fig. 8. Operational details of the power plant over 95 days of operation.

Table 4
Comparison of specific energy consumption and specific energy cost.

Parameter	Current operations at BERI	Reference Ravindranath et al. (2004)	Reference Ghosh et al. (2004)
Wood, kg/kWh	1.35	1.25	0.82
Diesel, kg/kWh	0.00	0.065	0.135
Energy contribution from wood, per kWh @ a calorific value of 15 MJ/kg	19.50	18.75	12.33
Energy contribution from diesel, per kWh@ a calorific value of 42 MJ/kg	0.00	2.32	4.82
Specific energy consumption MJ/kWh	19.50	21.07	17.15
Cost of biomass at 50 USD/t	6.75	6.25	4.11
Cost of diesel at 1 USD/L	0.00	6.50	13.50
Specific energy cost US c/kWh	6.75	12.75	17.61

manpower availability, biomass availability and also continuous rains at the project site during this period.

Fig. 9 presents specific fuel consumption over the period of operation. It can be seen that the average fuel consumption is in the range of about 1.3 kg/kWh, while the daily best has been in the range of 1.1 ± 0.1 kg/kWh.

Other benefits

Comparing the performance with the experiences in using biomass gasification, it is evident the current process is efficient in using local resources, i.e., biomass to generate electricity without any fossil fuel support. This is essentially a solution to the current issues on power for rural community in a sustainable way. It can be stated that all the economics related to transactions of biomass is within the village boundary, thus further strengthening the economic sustainability of the power project.

It must be recalled that the project site has an installed capacity of 880 kWe using biomass gasification for power generation for meeting local electrical energy needs. Karnataka state generates electricity largely from thermal power plants. Providing only biomass waste is used, there are no net CO_2 emissions from the biomass used in the gasifier and engine. Thus this technology can be considered CO_2 neutral. Offsetting the CO_2 generated using fossil fuel (coal), can be significant using this CO_2 neutral technology. With the current capacity of about 0.88 MW total power generation capability, annual electricity generation would be about 5.3 GWh at an overall plant load factor of about 68%. The current system may contribute very little towards the overall energy scenarios of the state but has significant value in terms of maintaining the grid voltage and reducing the losses. The net reduction of CO_2 is about 5.3 million tons when all the plants are operational.

Table 4 summarizes the specific energy consumption and specific energy cost for operations at BERI and compares with the performance data available in the literature. Specific energy consumption (SEC) is the energy input from different fuels used to generate one unit of electricity. Using the SEC, specific energy cost, which is the sum of cost of various fuels used to generate one kWh of electricity is estimated.

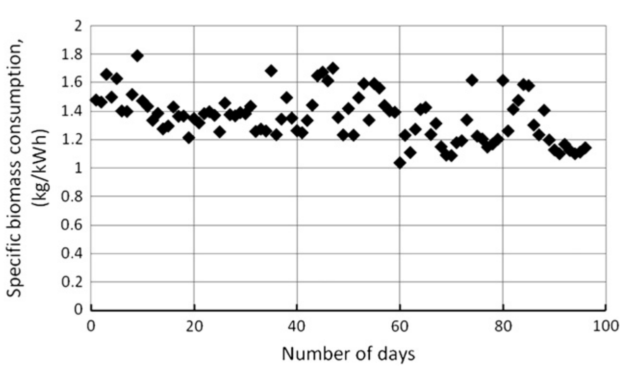

Fig. 9. Specific fuel consumption over 2000 h of operation.

The specific energy consumption based on the data from Ghosh et al. (2004) is lower due to dual-fuel operation approaching more efficient diesel based operating condition with only 60% diesel substitution by gas. Ravindranath et al. (2004), report diesel savings in excess of 75%. Table 4 consolidates the SEC and the cost for dual fuel and gas-only operation. It is clear that the gas engine operation at BERI is the lowest cost option to generate one kWh of electricity compared with dual fuel operation. The high diesel substitution reported in Ravindranath et al. (2004) is reflected in the specific energy cost being lower than that of Ghosh et al. (2004).

Rural electricity

Several attempts have been made towards ensuring distributed power generation using renewable energy devices (MNRE, 2010), like solar, gasifier, etc. Most of the interventions with solar PV have been as individual home systems, unlike a wired mini-grid electricity. The cost of grid electricity in an urban area is about 10–15 USc per kWh depending on usage — domestic or commercial. The grid cost in most of the rural sector in India is subsidized with effective cost to the rural consumer of less than 3 USc per kWh for a range of end users. Most of the grid distribution in India is carried out by respective states through Energy Service Companies (ESCOs) that are to be financially independent. There is a clear conflict between the revenues earned by the ESCOs and the subsidized electricity, which manifests itself in the quality of rural electricity service. It is important to address this policy barrier for the success of distributed power generation systems in India.

Conclusions

The paper has highlighted the operations of a remotely located biomass gasification power plant connected to a rural grid. The continuous operations have suggested that capability of small biomass based power generation system to deliver electricity of grid quality. Even at 100 kWe capacity, the overall efficiency of conversion has been shown to be about 18%, which reflects the best choice of technology for electricity generation using biomass in a distributed power scenario. The paper also presents the operations of total technology package from fuel processing to electricity generation, and meeting most of the statutory norms on emissions and discharge. If the power plant operates on an average at 750 kWe in operation, we estimate an annual reduction in CO_2 emissions of about 5.3 million tons. The specific energy cost is lower in the gas-only engine operation compared with dual fuel operation.

Acknowledgments

The authors would acknowledge the support of the BERI operational team and in particular Mr. Rangaraju for his effort in enabling the plant operational with stable grid connectivity. The authors also wish to place on record the excellent support by the technical team at CGPL, IISc.

References

Anon. Guideline for safe and eco-friendly biomass gasification. Europe: Intelligent Energy Publication; 2009 http://www.gasification-guide.eu/gsg_uploads/documenten/D10_Final-Guideline.pdf.

BERI. http://www.bioenergyindia.kar.nic.in [viewed Sept 2010].

Central Electricity Authority. Review of performance of thermal power stations 2005–06. Ministry of power, Report No. "CEA/GO&D/OPM/3oth Issue" 2006; 2006.

Dasappa S. On the estimation of power from a diesel engine converted for gas operation — a simple analysis. Proceedings of the seventeenth national conference on i.c. engines and combustion, Suratkal; 2001. p. 167–74.

Dasappa S. Energy from biomass. In: Hassan MN, Roy S, editors. Sustainable energy in Asia and the Pacific — emerging technologies and research priorities. Malaysian Academy of Sciences Publication; 2010. p. 89-108.

Dasappa S, Paul PJ, Mukunda HS, Rajan NKS, Sridhar G, Sridhar HV. Biomass gasification technology — a route to meet energy needs. Curr Sci 2004;87(7):908–16.

Dasappa S, Sridhar G, Sridhar HV, Rajan NKS, Paul PJ, Upasini Arvind. Producer gas engines — proponent of clean energy technology. Proceedings of 15th European biomass conference & exhibition – from research to market deployment – biomass for energy, industry and climate protection, Germany; 2005. p. 976–81.

Ghosh S, Das TK, Jash T. Sustainability of decentralized woodfuel-based power plant: an experience in India. Energy 2004;29:155–66.

Hammond AB, Kemausuor F. Guidebook on modern bioenergy conversion technologies in Africa. KNUST, Kumasi, Ghana: The Energy Centre; 2008.

KSPCB. Schedule VI, part a, general standards for discharge of environmental pollutants. In: Puliani Sathpal, editor. The environment (protection) rules 1986 — the environment protection and pollution control manual. Karnataka Law Journal Publication; 1986. p. 97–8.

Kumar N, Keshavan BK, Ahamed MN. A case study of improvements to a typical Indian rural distribution feeder, presented at the National Conference on Advances in Electrical Engineering; 2008.

MNRE. http://www.mnre.nic.in [viewed December 2010].

MoP. URL http://www.Powermin.nic.in [viewed August 2010].

Mukunda HS, Paul PJ, Dasappa S, Shrinivasa U, Sharan H, Buehler R, et al. Results of an Indo-Swiss programme for qualification and testing of a 300 kW IISc-Dasag gasifier. Energy Sustainable Dev 1994;1(4):46–9.

Ravindranath NH, Usha Rao K, Natarajan B, Monga P. Renewable energy and environment — a policy analysis for India. New Delhi: Tata McGraw-Hill; 2000.

Ravindranath NH, Somashekar HI, Dasappa S, Jaysheela Reddy CN. Sustainable biomass power for rural India: case study of biomass gasifier for village electrification. Curr Sci 2004;87(7):932–41.

Reddy AKN. Goals, strategies and policies for rural energy. Econ Polit Wkly 1999:3435–45.

Somashekar HI, Dasappa S, Ravindranath NH. Rural bioenergy centres based on biomass gasifiers for decentralized power generation: case study of two villages in southern India. Energy Sustainable Dev 2000;IV:55–63.

Sridhar G, Dasappa S, Sridhar HV, Paul PJ, Rajan NKS, Prakasam Kummar VS, et al. Green electricity—a case study of a grid linked independent power producer. Proceedings of 15th European biomass conference & exhibition – from research to market deployment – biomass for energy, industry and climate protection, Germany, October 2005; 2005a. p. 2256–61.

Sridhar G, Sridhar HV, Dasappa S, Paul PJ, Rajan NKS, Mukunda HS. Development of producer gas engines. J Automobile Eng D Proc Inst Mech Eng 2005b;219:423–38.

Srinivas SN, Ravindranath NH, Dasappa S, Shrinivasa U, Mukunda HS. Wood gasifier based rural power generation system: a case study. Pac Asian J Energy 1992;2:81–91 New series, Vol. 2, No. 2.