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Feasibility study of a biomass gasification based combined power and cooling plant for an off-grid village

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Abstract. This paper presents a feasibility study of a biomass gasification based combined power and cooling plant for an off-grid village to meet its energy needs in a sustainable way. The total electrical demand for a village has been estimated based on various applications. Based on the electrical demand, a biomass gasification based gas turbine (GT) unit of 100 kW net electrical output has been modelled. An ammonia absorption refrigeration unit has been integrated with the GT unit to recover the waste heat and to run a cold storage. This plant has the capability of producing a cooling effect varying in the range of 150-400 kW. The combined cycle plant has a predicted maximum electrical efficiency of 23%, for a GT cycle pressure ratio of 8 and a GT inlet air temperature of 1000°C. The refrigeration capacity of the plant at this condition is 150 kW and the corresponding biomass consumption is 96 kg/h. It has been shown that the plant has the capability of meet the electrical demand of the village as well as to run a cold storage, considering 8-10 hrs of daily operation time.

1. Introduction
One of the primary needs for socio-economic development of any developing country is the provision of reliable electricity supply systems. But millions of people in the developing nations still live in areas that are far away from the grid [1]. In most of the remote and non-electrified sites, any effort towards extension of utility grid lines meets with a number of problems, such as, high capital investment, longer lead time, low load factor, poor voltage regulation, greater transmission losses and frequent power supply interruption. Thus the installation and distribution costs become higher and consequently, unit cost of electricity increases. Hence, there is a need to search for decentralized and renewable energy options to meet the rural energy need in a sustainable way. Among the renewable energy sources, biomass is one of the most promising and readily exploitable resources. In India, about 32 % of the total primary energy use is still derived from biomass and more than 70 % of the country’s population depends upon it for their energy needs and, therefore, biomass-energy technologies have been promoted by the Government for meeting rural electricity needs [2].

Biomass is available in various forms as forest residues (bark, branches, twigs, leaves and wood), plants like sugarcane, bamboo, eucalyptus and a verity of tree species, agricultural residues (rice husk, straw), animal waste, industrial waste (wood chips, saw dust) and municipal solid waste. The conversion of biomass to biofuel can be achieved by different methods such as thermal, chemical and biochemical methods. Biomass gasification is one of the best processes of biomass energy conversion. Biomass gasification is a thermochemical process in which solid biomass is partially oxidized at high temperature into combustible gas mixture known as producer gas. The major components of the
producer gas are CO, H$_2$, CH$_4$, CO$_2$, water vapour and N$_2$. Gasifying agents (air, enriched air, steam, oxygen) and the operating conditions controls the quality of the producer gas. The lower heating value (LHV) of producer gas is about 4-6 MJ/N m$^3$, when air is used as gasifying agent. The LHV is much higher (12-18 MJ/N m$^3$) when steam or oxygen is used as a gasifying agent [3, 4]. The producer gas is used in internal combustion engines and gas turbines as fuel. Biomass gasification based gas turbine (GT) has higher power generation efficiency than biomass gasification based internal combustion engines [5]. But the problem with this type of system is that a large amount of heat loss takes place due to high temperature turbine exhaust. Integration of bottoming unit, producing power or cooling effect, utilizing the waste heat, can improve the performances of the system and can meet the demand of electricity and cooling effect simultaneously [6, 7].

This paper presents a feasibility study of a biomass gasification based combined power and cooling plant for an off-grid village. For this purpose, a biomass gasification based indirectly heated combined cycle plant, employing a GT unit and a vapour absorption refrigeration (VAR) unit (using ammonia-water solution) has been modelled using Cycle-Tempo process simulation software [8]. The maximum capacity of the GT plant is determined by analyzing the probable electrical loads. Based on the available waste heat of power producing GT unit, the capacity of the cooling unit has been determined.

2. Plant description
The schematic diagram of the biomass gasification based combined power and cooling plant is shown in Figure 1. Solid biomass is fed to a gasifier and gasification occurs in presence of atmospheric air in sub-stoichiometric condition. The producer gas undergoes combustion in the combustor in presence of hot exhaust air of the gas turbine. The combustion products then enter the heat exchanger and flows through the shell side of it. Clean compressed air gets heated in the heat exchanger and then expands in the turbine, producing power in the generator. A low pressure heat recovery steam generator (HRSG) is used to recover waste heat from the flue gas. The HRSG sub-units are drum, evaporator, feed pump and economiser. The steam produced in HRSG is used to supply heat to the generator of a vapour absorption refrigeration (VAR) plant. The VAR plant runs on aqua-ammonia absorption cycle.

![Diagram of biomass gasification based combined power and cooling plant](image-url)

**Figure 1.** Biomass gasification based combined power and cooling plant
3. Load estimation and forecasting
The various electrical applications, their wattages, working hours and contribution to the total load have been shown in the Table 1. In this study, considering low voltage transmission line within the village, it is assumed that 20% loss of the total estimated load as line and other losses.

**Table 1. Load estimation for the village**

| Application         | Number | Watt  | Working hours | Load (kWh/day) |
|---------------------|--------|-------|----------------|----------------|
| Tube light          | 200    | 40    | 5              | 40             |
| Fan                 | 100    | 65    | 16             | 104            |
| TV                  | 10     | 300   | 4              | 12             |
| Pump                | 10     | 1500  | 6              | 90             |
|                     |        |       |                |                |
| **Sub-total (residential sector)** | 246    |       |                |                |
| Tube light          | 10     | 40    | 5              | 2.0            |
| Fan                 | 5      | 65    | 5              | 1.625          |
|                     |        |       |                |                |
| **Sub-total (primary school)** | 3.63   |       |                |                |
| Tube light          | 25     | 40    | 6              | 6.0            |
| Fan                 | 25     | 65    | 6              | 9.75           |
| Pump                | 1      | 1000  | 2              | 2.0            |
| Computer            | 5      | 600   | 4              | 12             |
|                     |        |       |                |                |
| **Sub-total (higher secondary school)** | 29.75  |       |                |                |
| Tube light          | 4      | 40    | 8              | 1.28           |
| Fan                 | 2      | 65    | 8              | 1.04           |
|                     |        |       |                |                |
| **Sub-total (health centre)** | 2.32   |       |                |                |
| Tube light          | 5      | 40    | 6              | 1.2            |
| Fan                 | 3      | 65    | 6              | 1.17           |
| Computer            | 1      | 600   | 4              | 2.4            |
|                     |        |       |                |                |
| **Sub-total (gram panchayat)** | 4.77   |       |                |                |
| Tube light          | 8      | 40    | 10             | 3.2            |
| Fan                 | 6      | 65    | 10             | 3.9            |
| Computer            | 4      | 600   | 10             | 24             |
|                     |        |       |                |                |
| **Sub-total (bank)** | 31.10  |       |                |                |
| Tube light          | 2      | 40    | 5              | 0.4            |
| Fan                 | 1      | 65    | 5              | 0.325          |
|                     |        |       |                |                |
| **Sub-total (post office)** | 0.73   |       |                |                |
| CFL                 | 30     | 40    | 5              | 6.0            |
|                     |        |       |                |                |
| **Cold storage**    | 0.4    |       |                |                |
| CFL                 | 10     | 20    | 2              | 0.4            |
| Pump                | 1      | 1000  | 1              | 1.0            |
| Solution pump (VAR)| 2      | 1500  | 20             | 60             |
|                     |        |       |                |                |
| **Sub-total (cold storage)** | 61.4   |       |                |                |
| **Total electricity load of the village (without line loss)** | 385.70 |       |                |                |
| **Total electricity load of the village (considering line and other losses)** | 462.84 |       |                |                |
It is considered that the village consists of fifty houses, a primary school, a higher secondary school, a bank, a health centre, a gram panchayat, a post office and a cold storage. It is also assumed that there will be two fans and four lights in each house. Pumps that are listed in the residential sector are mainly used for agricultural purpose. There will be thirty CFL lights to illuminate the streets. The total electrical load of the village is calculated based on these considerations. The cold storage needs electricity for its pumps (water pump and solution pump of VAR unit) and lighting purpose only.

The electricity demand of the village will gradually increase over the years. Hence, the design capacity of the plant should be decided on the basis of the present scenario of demand and taking into account possible growth of demand. In this study, a growth forecast for five to six years has been considered for the village and accordingly the loads in various sectors have been increased by a certain percentages \[9\], as shown in Table 2.

| Sector                  | Load growth after five years | Load (kWh/day) after five years |
|-------------------------|------------------------------|--------------------------------|
| Residential             | 20 %                         | 295.2                          |
| Primary school          | 10 %                         | 4.0                            |
| Higher secondary school | 10 %                         | 32.73                          |
| Health centre           | 5 %                          | 2.44                           |
| Gram panchayat          | 10 %                         | 5.25                           |
| Bank                    | 20 %                         | 37.32                          |
| Post office             | 5 %                          | 0.77                           |
| Street light            | 15 %                         | 7.0                            |
| Cold storage            | 5 %                          | 64.5                           |
| Total forecasted load   |                              | 449.21                         |
| (without line loss)     |                              |                                |
| Total forecasted load   |                              | 539.06                         |
| (taking 20 % loss into consideration) |                      |                                |

4. Determination of plant capacity

The plant capacity is to be determined based on the estimated forecasted load (539.06 kWh/day). The maximum power demand at any point of the time can be determined as follows:

\[
\text{Maximum power demand} = \frac{\text{Load per day}}{\text{Load factor} \times 24} \tag{1}
\]

In this study the load factor is assumed as 0.5 \[10\]. From Equation (1), the calculated plant capacity stands at 45 kW. The maximum capacity of the plant is decided by adding 15 % to the calculated capacity, to take into account uncertainties of the forecasted data. Thus the peak demand becomes 52 kW. Considering 8-10 hrs of operation in a day, a plant of 100 kW will be sufficient to meet the peak demand as well as the total daily consumption. Thus, an installation capacity of 100 kW GT unit has been considered in present study. Cycle-Tempo process simulation software has been used to develop the model of the plant. For the VAR cycle, the evaporator temperature and the generator temperature are set to fixed values of -10°C and 120°C, respectively. Based on the available waste heat of the power producing GT unit, the capacity of the cooling unit is determined.

5. Plant performance and discussions

The important performance parameters that could be used to determine the plant performances and the corresponding results are discussed in this section.

The GT unit is only the power producing unit in this plant. The feed pump of HRSG and the solution pump of VAR unit consume power. The electrical efficiency of the plant is defined as the ratio of net electrical output of the plant to the fuel energy input to the plant. The cooling-to-power ratio (CTPR) is the ratio of cooling capacity of the VAR unit to the net electrical output of the plant.
The electrical efficiency ($\eta_e$) of the plant is calculated as

$$\eta_e = \frac{W_E - W_{FP} - W_{SP}}{m_b \times \text{LHV}_b}$$  \hspace{1cm} (2)

where $W_E$ is the net power output (kW) of the gas turbine (GT) unit and $W_{FP}$ and $W_{SP}$ are the work consumed by the feed pump of HRSG and solution pump of VAR unit, respectively. In this equation $m_b$ is the biomass consumption rate (kg/s) and LHV$_b$ is the lower heating value (kJ/kg) of biomass.

The cooling-to-power ratio (CTPR) of the plant is given by

$$\text{CTPR} = \frac{Q_E}{(W_E - W_{FP} - W_{SP})}$$  \hspace{1cm} (3)

where $Q_E$ is the cooling capacity (kW) of the VAR unit.

The coefficient of performance (COP) of the VAR unit can be written as

$$\text{COP} = \frac{Q_E}{Q_G + W_{SP}}$$  \hspace{1cm} (4)

where $Q_G$ is the amount of heat required (kW) in the generator of VAR unit.

The performances are assessed over a range of GT cycle pressure ratio ($\text{PR} = 2$ to 16) and GT inlet air temperature ($\text{TIT} = 900$-$1000^\circ$C). Figure 2 reveals the effect of GT cycle pressure ratio on electrical efficiency ($\eta_e$) of the plant. The plant shows maximum electrical efficiency of 23 % at a value of PR = 8 and TIT = $1000^\circ$C. At this condition the plant has minimum biomass consumption rate of 96 kg/h. The variation of cooling-to-power ratio (CTPR) with GT cycle pressure ratio is shown in Figure 3. At the condition of maximum electrical efficiency, the plant shows minimum cooling capacity of 150 kW (about 40 TR). The COP of the cooling unit is 0.6 and does not changes with change in PR and TIT as the operating temperature for both the evaporator and the generator are fixed.

Thus the optimum GT pressure ratio is 8 and the GT inlet air temperature is considered as $1000^\circ$C for design point operation. The plant performances at the design point are shown in Table 3.
Table 3. Performance of the plant at maximum efficiency condition (design point operation)

| Parameters                              | Unit | Value |
|-----------------------------------------|------|-------|
| Electrical output of the plant          | kW   | 100   |
| Electrical efficiency of the plant      | %    | 23    |
| Cooling capacity of the plant           | kW   | 150   |
| Cooling-to-power ratio (CTPR)           | -    | 1.5   |
| COP of VAR unit                        | -    | 0.60  |
| Final exhaust gas temperature          | °C   | 125   |
| Biomass fuel input to the plant         | kg/h | 96    |

6. Conclusions

In this work, a feasibility study of a biomass gasification based combined power and cooling plant for an off-grid village has been carried out. Considering the probable loads from all the sectors of a village community (having fifty houses), a load estimation has been performed and a load forecasted for the next five years has been done. The required capacity of the plant to meet the demand of the village is determined to be 100 kW (considering 8-10 hrs daily operation time). A biomass gasification based indirectly heated combined cycle plant, employing a GT unit and a vapour absorption refrigeration (VAR) unit (using ammonia-water solution) has been modelled. The plant shows the maximum electrical efficiency of 23% with minimum biomass consumption of 96 kg/h at a GT cycle pressure ratio of 8 and GT inlet air temperature of 1000°C. At this point the plant can carry a cooling load of 150 kW cold storage, using the waste heat of GT unit. Thus a 100 kW biomass gasification based GT plant is sufficient to meet the basic demand of the village and at the same time can support a cold storage of about 40 TR capacity.

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