Small-scale CHP for Rural Electrification in Uganda – The State-of-the-art and Prospective Development

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ABSTRACT
Worldover, small-scale CHP systems are undergoing rapid development, and are emerging on the market with promising prospects for the near future. The choice of a suitable CHP system is driven by the need and local conditions at the target end user, keeping in mind that the system integration should have a good balance of being most efficient, reliable, cost effective, socially beneficial, least polluting and sustainable in the long run. In developing countries, small-scale biomass-fuelled CHP systems have a particular strong relevance in improving the quality of life, especially among rural communities. This paper presents the recent advances in small scale CHP process integration for decentralized power generation. It also presents an exergy analysis of a prospective CHP system that has the potential of providing relatively higher efficiency and minimal operational difficulties and thus attractive for rural electrification in Uganda. The target generation capacity is 100 kWe sufficient to meet electricity needs of a rural community of 250 households. Stepwise procedure with simulation using Aspen Plus is used in the analysis of this CHP cycle. The results show that the proposed process integration has the promise of efficiently utilizing the exergy generated.

Keywords: Decentralized generation; Indirectly fired microturbine; Small-scale CHP; Steam gasification

1.0 INTRODUCTION

The majority of Uganda's population has no access to electricity particularly in rural areas. Increasing access to electricity is considered a high priority and a major challenge to the government of Uganda and other stakeholders. Several policy interventions to address this challenge have been developed such as the Renewable Energy Policy (2007), whose main goal is to increase the use of modern renewable energy from the current 4% to 61% of the total energy consumed by 2017 (MEMD, 2009) and the Rural Electrification Strategy and Plan, 2001 to 2011. However, there is still limited progress especially in rural electrification. Indeed, Uganda ranks among the lowest in terms of access to electricity, with about 3% in rural areas (MEMD, 2007). Connecting the majority of the rural communities to the national grid is not feasible at present considering that it is uneconomical in extending the conventional grid power line to remote areas and there is also limited capacity on the grid. It is recognized by key players in energy sector that putting emphasis on small decentralized power generation will contribute to achieving increased access to electricity in remote areas. In line with global demands of environmentally friendly electricity generation through reduction of carbon footprint, renewable sources of energy are top priority. Comparing renewable energy sources available in Uganda, biomass has an edge in terms of wide availability coupled with high energy concentration. Buchholz and Da Silva (2010) compared various options suitable for providing electricity to rural community and concluded that distributed small-scale biopower creates the most economic opportunities within the community even though the use of this technology is still in its infancy stage in Uganda. Uganda has one of the highest bioenergy potential in the world (Hoogwijk *et al*., 2005). It is estimated that sufficient biopower production to cover basic community electricity services would require only 0.03 ha/person or 4% of the available productive land (Buchholz and Da Silva, 2010). CHP has been considered worldwide as the major alternative to conventional systems in terms of significant energy saving and environmental conservation (Denntice et al., 2003; Okure *et al*., 2006). In developing countries, small-scale biomass-fuelled CHP systems have a particular strong relevance in improving the quality of life, especially in rural communities (Leilei *et al*., 2008). Innovative systems which are site specific have shown great success in other countries.

A gasification-based CHP system can potentially have higher electricity efficiency than a direct combustion-based CHP system (Leilei *et al*., 2008; Juan et al., 2010; Puig-Arnavat *et al*., 2010). A further advantage is that gas firing produces less CO_2 per unit power than does a liquid or solid fuel (Pilavachi, 2000). As is well known, during biomass gasification process, the component distribution in the producer gas depends on the fuel type, reactor configuration, gas–solid residence time, reaction temperature, pressure, gasifying agent and catalyst. Among these factors, the type of reactor and gasifying agent play a key role in determining products distribution and gas compositions of biomass gasification (Ligang *et al*., 2006). The technology of biomass air gasification is widely viewed to be more feasible and has been developed actively for industrial applications. However this technology produces a gas with a low heating value (4–6 MJ/Nm^3) and an 8–14 vol. % H_2 content (Delgado and Aznar, 1997). Biomass oxygen-rich air gasification is one effective way of producing medium heating value (MHV) gas with a heating value of 10-18 MJ/Nm^3 (Schuster, 2001), but it needs a large investment for oxygen production equipment and this disadvantage impedes its popularization (Lv *et al*., 2004). Steam-gasification processes (with or without O_2 added) are also capable of producing a MHV (10–16 MJ/Nm^3) gas with a 30–60 vol% H_2 content (Mathieu and Dubuisson, 2002). The addition of steam as gasifying agent and catalyst in gasification process makes it possible to obtain high-grade and nearly N_2-free product gas (Ligang *et al*., 2006; John *et al*., 2008).

The producer gas can be appropriately utilized in an indirectly fired micro gas turbine (25-250 kWe) (Vollrad *et al*., 2008) integrated with a high temperature heat exchanger for efficient power generation. In microturbine systems the two parameters that have potential for efficiency advancement are increased values of turbine inlet temperature and higher heat exchanger effectiveness. The major aspects to consider in heat exchanger design are the optimization of the heat transfer surface geometries and the material type that can withstand high temperatures.

2.0 OVERVIEW OF SMALL-SCALE CHP PROCESS INTEGRATION

The commonly known small-scale CHP systems make use of microturbines, reciprocating engines (internal combustion engines, Stirling engines (external combustion engines) and fuel cells as their electricity generation technologies. In microturbines, it implies that the CHP unit is using a gas turbine with electrical power generation from 25 to 250 kW with exhaust gas temperature above 450^{o}C. The great advantage of microturbines is that they are compact, clean and highly efficient. Another unique feature of microturbines is that many of them adopt a full digital power control system that allows for a variable shaft speed operation, while producing electricity with a constant frequency (Jong *et al*., 2009). The benefit of the variable speed operation is to yield much higher part load efficiency in comparison with a constant speed operation (Kesseli *et al*., 2003 as cited by Kim and Hwang, 2006). Taki et al (1991) developed a mathematical model to describe the behaviour of small-scale CHP units and concluded that under similar operating conditions, a CHP unit based on micro gas turbine is more competitive than that based on reciprocating engines.

A reciprocating engine (e.g. gas engine) can be quite efficient in producing electricity but sometimes has the drawback of requiring regular maintenance and servicing. The carbon emission levels can be high in gas engines if not well maintained. The Stirling engine is a reciprocating engine with its cylinder closed and combustion taking place outside of the cylinder. The Stirling engine has relatively low electrical efficiency (approx. 15%) when solid biomass is used as fuel (Peacock and Newborough, 2005). A fuel cell produces electricity electrochemically, by combining hydrogen and atmospheric oxygen. The electrical efficiency of these systems can be as high as 45–55% (Alanne and Saari; 2004). However the draw back in using fuel cell is the high cost of hydrogen production and storage. The other available options for small/micro scale biomass CHP generation are Organic Rankine Cycle (ORC) turbine and steam engine but these are less competitive for small scale applications.

2.1 Related Work on Innovative small-scale CHP Integration

Gaderer *et al*. (2010) reports on ongoing work at the Institute for Energy Systems, Technische Universität München, comprising of the biomass fired hot air gas turbine, a fluidized bed wood combustor with integrated high temperature heat exchanger out of structured steel tubes for indirect firing of micro-turbines at100 kWel. Al-attab and Zainal (2009) developed a small-scale CHP Indirectly fired gas turbine system that incorporated air gasification of wood. Their main focus was to study the performance of the high-temperature heat exchanger at different air pressures and flow rates. They achieved 694 ^{o}C turbine inlet temperature and concluded that increase in turbine inlet temperature is possible with consideration of various heat exchanger designs. Kautz and Hansen (2007) studies the externally-fired gas-turbine cycle for decentralized generation based on solid biomass combustion. They studied the effects of temperature difference and pressure loss in the gas-to-air heat exchanger of cycle output. Daniele *et al*. (2005) evaluated the performance of a small scale externally fired gas turbine fuelled by residual biomass and integrated with a biomass dryer. They considered hot compressed air heated in the high temp heat exchanger using hot gases from direct combustion process. The exhaust heat was recovered by drying the raw biomass in a rotary dryer. They concluded that use of dry biomass allows for efficiency values of 22-33% and that the electrical efficiency increases as the turbine inlet temperature increases from 22.5% at 800^{o}C to 33.3% at 1200^{o}C.

Delattin *et al*. (2007) examined the effects of steam injection on microturbine behaviour by simulating its off-design characteristics in Aspen. They found out that a large steam addition increases the electric efficiency provided the amount injected does not exceed the surge limit.

Kentaro *et al*. (2010) performed experiments of steam gasification of wood in an updraft fixed bed gasifier. The process integration also consisted of a reformer, a high temperature steam heater utilizing propane gas, heat exchangers and gas cleaning equipment. The ideal cold gas efficiency of the whole system with heat recovery processes was 71%.

3.0 CHP SYSTEM INTEGRATION AND THERMODYNAMIC ANALYSIS

3.1 System Description

The main components of the system include; the gasifier, producer gas combustor/heat exchanger, indirectly fired gas turbine and heat recovery steam generator. The cycle involves steam gasification of woody biomass in a fixed bed downdraft gasifier and the producer gas obtained is then led to a combustor integrated with a heat exchanger. Compressed air and steam mixture is heated up in the high temperature heat exchanger to turbine inlet temperature. The exhaust gases from the turbine are led to a heat recovery steam generator. The generated steam is used for both injection into the gas turbine as well as a gasifying agent. Flue gases from the combustor are used for preheating the combustion air. Figure1 shows the CHP system proposed in this paper.

An indirectly fired gas turbine was preferred because the gas turbine operates on a clean working medium (air plus a small portion of steam), thereby minimizing wear and other potential damage to turbine blades. Burning producer gas in the combustor has an edge over the solid biomass because the gaseous fuel offers high heat exchanger temperature as well as stable combustion/continuous operation. It is also easy to control the flow of fuel and oxidant in combustion of a gaseous fuel for optimal output. Burning of solid fuel would cause erosion of the heat exchanger surfaces much faster than producer gas. Therefore gasifying the biomass to obtain a combustible gas is essential. The downdraft gasifier is the most commonly used type in small-scale energy production because of its simplicity and reliability. Its fuel power input ranges from around 100 kW to 1 MW. The gasifier fuel power range satisfies the target electric power output of 100 kW in this research.

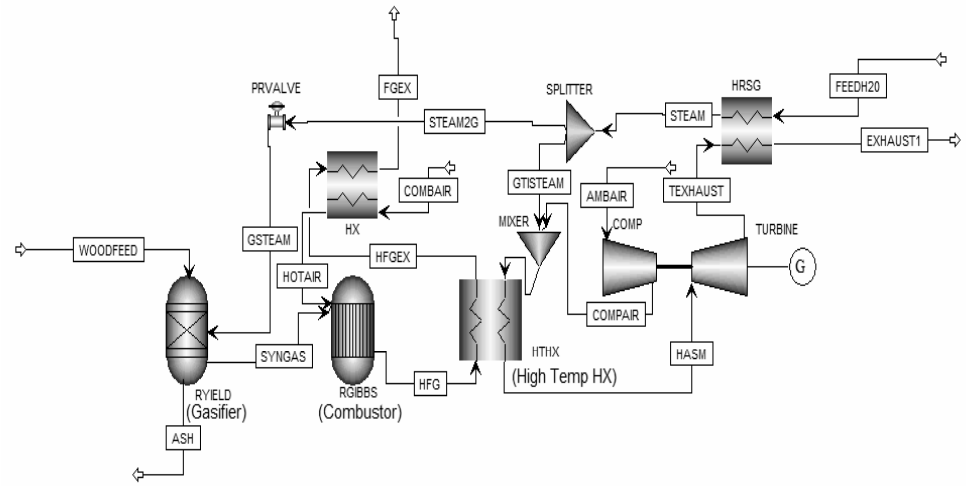

Figure 1: Schematic diagram of the CHP Configuration

3.2 Thermodynamics Analysis

The thermodynamics analysis of this system considers continuous deterministic steady-state conditions. Stepwise procedure with simulation using ASPEN PLUS process modeling is used in the thermodynamic analysis of the cycle. The ASPEN PLUS Gibbs reactor was used for producer gas combustion with the assumption that the reaction follows the Gibbs equilibrium. The process parameters in this CHP cycle are correlated with those available in the literature by (Schuster *et al*., 2001; Mathieu and Dubuisson, 2002; Kentaro *et al*., 2009; Chiaramonti *et al*., 2004; Franco *et al*., 2003; Acharya *et al*., 2010; Kautz *et al*., 2007; Daniele *et al*., 2005; Dellatin *et al*., 2010). These parameters represent commercially available technologies or processes in advanced development stage.

The gasifier is fed with 0.02 kg/s of wood (19 MJ/kg HHV, 10% moisture). This yields 0.064 Nm^3/s of producer gas based on allothermal steam gasification. A steam/biomass ratio in the range 0.5-0.9 w/w is appropriate for optimal generation of a hydrogen rich producer gas (Kentaro *et al*., 2009). Since steam gasification is an endothermic reaction, approximately 20% of the producer gas is re-circulation back to the gasifier core to provide the heat for the process under allothermal gasification conditions. Allothermal gasification is preferred to autothermal gasification in order to avoid dilution of producer gas leading to the combustor. This also helps in avoiding large flow into the heat exchanger and thus causing design difficulties. The available producer gas for power production is 0.0512 Nm^3/s with estimated lower heating value of 14 MJ/Nm^3 and components (by volume); H_2-53%, CO-25%, CH_4-2%, CO_2-10%, and H_2O-10%. Presence of water vapour and carbon dioxide molecules is due to the water-gas shift reaction during the gasification phase. The presence of nitrogen is negligible evident with Ugandan woody biomass with less than 0.3 % Nitrogen based on ultimate analysis. The hot producer gas (700^{o}C) is led into an adiabatic Gibbs reactor together with preheated combustion air (200^{o}C) in excess of 30%. The steam addition into the compressed air is limited to 5% of the mass of airflow in order to keep within the surge limits of steam injection in microturbines. The overall process parameters are shown in Table 1.

Table 1: Process parameters

Parameter	Value	Parameter	Value
Flow rates		**Pressure**	
Wood feed rate	72 kg/h	Ambient (Air, Feedwater and RGibbs	
Steam/feedstock ratio	0.9 kg/kg	HX, Gasifier, turbine exhaust	1 bar
Producer gas flow to RGibbs	112.5 kg/kg	Compressor pressure ratio	4.5 bar
Air/producer gas ratio	5.2 kg/kg	Steam exiting HRSG	4.5 bar
Air flow to compressor	1,944 kg/h	Steam injected in microturbine	4.5 bar
Steam injected into the	97.2 kg/h	Gasifying steam	1 bar
Microturbine (5% of air flow)		Pressure loss across HXin	5%
Steam flow from the HRSG	288 kg/h	turbine working fluid	
Excess steam available	126 kg/h	**Power**	
Temperatures			
Ambient (air, feedwater, wood)	25°C	Thermal power input of the	340 kw
Gasification Zone	850°C	gasifier (m wood XLHV wood)	
Gasifying steam	500°C	Net electric output with steam	122.4 kw
Producer gas exit to RGibbs	700°C	injection	101.9 kw
Combustion air to RGibbs 250◦C		Net electric output with steam injection	
Compressed air exit	225°C		
Steam injected in compressed air	500°C	**Efficiencies**	
Combustion gases to HX	1157°C	Isentropic, Compressor, Turbine	80%, 82.5%
Turbiner inlet	950°C	Mechanical	98%
Turbine exhaust to HRSG	587°C	Turbogenerator	92%
Superheated steam from HRSG	500°C	Electrical (with steam injection)	36%
Minimum approach in HX	100°C	Electrical (without stream injection)	30%
		High Temp HX effective	0.86
		Preheater effectiveness	0.86

4.0 RESULTS AND DISCUSSION

Steam injection can significantly increase the power output of the microturbine. In this cycle with a target electric power of 100 kW, air/steam mass ratio of 20 increased the power output from 101.9 to 122.4 kW and efficiency from 30% to 36%. Steam gasification yields a medium heating value gas that is responsible for the high exergy available in the combustor and thus the required microturbine working medium can be heated to turbine inlet temperatures. To effectively utilize the system's exergy, opportunities for heat recovery have been realized through generating the required steam from within the exhaust heat. Steam generation from high grade turbine exhaust is crucial for both steam gasification and steam injection into the turbine both of which contribute to increased exergy value of the system. The pressure of the steam leaving the single pressure heat recovery steam generator (HRSG) is 4.5 bar, which is equal to the pressure of the air exiting the compressor. This simplifies the mixing of the two streams before they enter the high temperature heat exchanger. Then the pressure of gasifying steam is reduced from 4.5 bar to 1bar by a pressure relief valve (PRV) in order to meet conditions of atmospheric fixed bed steam gasification. Exhaust gases from the high temperature heat exchanger leave at a high temperature of 377^{o}C. This is due to high temperature (250^{o}C) of the cold stream mixture of compressed air and steam entering the heat exchanger and the effectiveness limitations of the heat exchanger. However this high temperature exhaust is utilized in preheating the combustion air from ambient state to 250^{o}C. The flue gas exhaust temperature to the atmosphere is kept above 150^{o}C to prevent any possible condensation of sulphuric acid in the tubes. The sulphuric acid may result from the small amount of sulphur (0.05%) found in Ugandan woody biomass. The turbine exhaust (air and steam) leaving the HRSG is also kept close to 100^{o}C to avoid any water condensation in the tubes though the dew point of water in the mixture is 40^{o}C.

5.0 CONCLUSIONS

From the preliminary analysis, the results show that the proposed cycle is feasible with self-sustaining heat generation and recovery to satisfy the process goals. The cycle also demonstrates the potential of obtaining relatively high electrical efficiency. The design problem is thus optimizing a combination of gasification and proceeding energy conversion processes that give desirable operating conditions together with a high net conversion efficiency. It is possible to increase the efficiency if specific cycle parameters arising from extensive process study are utilized. CHP systems still suffer from technical uncertainties namely operational difficulties, poor reliability and low overall efficiency which requires considerable technical advances prior to commercial viability. Therefore, there is a research need to overcome the existing technical obstacles, and to demonstrate energy-efficient biomass-fuelled CHP systems. Further work in this research will be geared towards addressing the challenges of designing highly efficient combustor/high temperature heat exchanger integration and investigating steam gasification in downdraft fixed bed gasifier through extensive parametric modeling as well as carrying out thermoeconomic analyses of the cycle.

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The Smart grid: adopting new concepts for infrastructure to power Africa's emerging industrial revolution

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ABSTRACT

African economies are emerging among some of the world's best performers and set on course for imminent industrial revolution. This will however require more secure and affordable electricity supplies among other infrastructure. The centrally controlled power utility model as conceived by Nicola Tesla in the1880's has served the world well for just over a century and a quarter and been pivotal in the evolution of currently developed economies. But with emerging 21st century demands such as efficiency, environmental sustainability and consumer choice the model is reaching its limitations. Towering power lines traversing the countryside have traditionally presented imagery of development and advancement but are very capital intensive and incur massive power losses. A whole range of ecological and biodiversity issues along the routes of large power lines are also well documented.

Solutions for development in the developing world need not follow the same path as the developed world. Instead, relevant technical solutions for advanced applications in the developed world can be used to leapfrog intermediate technologies and applied directly, with benefit to the developing countries.

New trends are emerging both in energy supply economics and power management technologies. The most popular theme is the Smart Grid. The vision is comprised of three key elements namely, consumer empowerment, grid integrated distributed renewable resources and intelligent network logistics. The use of distributed resources particularly aims to reduce the need to invest in transmission infrastructure by positioning power generation closer to the load centers. In this paper the authors show through a case study of Tete province (Mozambique) that rather than taking generators to the load, new industrial centers should instead be built close to energy resources. Savings from the deferred transmission infrastructure could instead be used to construct manufacturing industry. Africa is particularly advantaged because unlike the developed world it does not have old infrastructure backlog. This presents a golden opportunity to plan using modern scientific concepts.

Keywords: Smart grid; renewable energy; distributed generation; power grid planning; infrastructure

1.0 INTRODUCTION

African postcolonial pioneers such as Kwame Nkrumah, Abdel Gamal Nasser and Julius Nyerere initiated the dream of a United States of Africa more than a half a century ago. In recent times the idea gained new momentum, through such initiatives as the New Partnership for African Development (NEPAD) and the African Union (AU). The objective is to create a single African market, now estimated at over a billion people, that is competitive within itself and at