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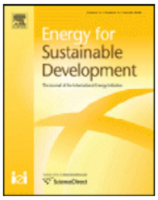

# Potential of biomass energy for electricity generation in sub-Saharan Africa

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ABSTRACT

The paper explores the biomass based power generation potential of Africa. Access to electricity in sub-Saharan Africa (SSA) is about 26% and falls to less than 1% in the rural areas. On the basis of the agricultural and forest produce of this region, the residues generated after processing are estimated for all the countries. The paper also addresses the use of gasification technology – an efficient thermo-chemical process for distributed power generation – either to replace fossil fuel in an existing diesel engine based power generation system or to generate electricity using a gas engine. This approach enables the implementation of electrification programs in the rural sector and gives access to grid quality power. This study estimates power generation potential at about 5000 MW and 10,000 MW by using 30% of residues generated during agro processing and 10% of forest residues from the wood processing industry, respectively. A power generation potential of 15000 MW could generate 100 terawatt-hours (TWh), about 15% of current generation in SSA. The paper also summarizes some of the experience in using the biomass gasification technology for power generation in Africa and India. The paper also highlights the techno economics and key barriers to promotion of biomass energy in sub-Saharan Africa.

## Introduction

Among other resources in a society, access to electricity is considered an important factor in development in any region. Centralized electricity generation and distribution are essential trends of a modern society. Hydro and thermal routes contribute a major share of electricity generation and only marginal support comes from other resources like nuclear and renewables.

IEA (2009) highlights the low level of electricity access in Africa and compares the situation with that prevailing in other continents. With electrification rate at 25% the population without electricity is 587 million and, Africa has the lowest level of electrification in the developing world. In China and East Asia, electrification rate is 90.8% compared to south Asia at 62.2%, Latin America at 93.4%, and the Middle East at 89.5%.

Disparities exist in the levels of electrification between North Africa (93.6%) and sub-Saharan Africa (23.6%) (Kauffmann, 2005). Taking into account the desire to improve electrification expressed by the International Energy Agency, Kauffman suggests that developing countries should be at least 95% electrified by 2030, with 51% in sub-Saharan Africa (SSA). In the SSA region, rural populations are the least served, with just 1% having access to electricity. Further the transmission and distribution losses are higher in Africa compared to the world average (11.3% compared to 9.2%). These losses exceed 20% in Senegal, Kenya and Tanzania and 40% in Nigeria and Congo.

It is important to highlight that distributed power generation is gaining importance in regions where electricity demand is high and supply is limited. A study by Kumar et al. (2008) clearly indicates the issues related to grid electricity when demand is high and the supply is short, manifested in poor quality electricity and increased losses while using the grid. Intervention by distributed power generation can reduce these losses and improve the quality of electricity.

Kooijman-van Dijk and Clancy (2010)analyze the impact of electricity access in Bolivia, Tanzania and Vietnam and show evidence that access to electricity in productive enterprises is having a stronger impact on non-financial aspects of poverty through the products and services of the enterprises than on financial poverty reduction through increasing incomes from the operation of enterprises. With agriculture as the energy end-use sector, where person days are secured for agricultural operation in the farmer's land, this aspect needs renewed thinking, on the basis of the study by Chanakya et al. (1996) which showed that the yield per unit area land irrigated increased over 10 times due to water availability. Chanakya et al. (1996) had carried out this study in a semi-arid land where water table is generally low and also the rainfall.

Among various renewable energy resources, biomass-based power generation systems can provide grid quality firm power (Dasappa et al. 2007). Biomass, a renewable energy source, is carbon, hydrogen and oxygen complex with small amount of nitrogen. The term Biomass is commonly identified as biological material from living plant or dead plant. In the present context biomass refers to dead

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trees, branches and tree stumps, yard clippings, off-cuts, wood chips and agro residues. Typical forest produce grown for timber has lops and tops amounting to about 35% of the timber extracted as wastes and this could be a substantial amount in a timber generating country. It is worth noting that biomass is stored solar energy and is available throughout the year. Biomass based power plants operating throughout the year with plant load factors in excess of 70% are conceivable and this would make their performance comparable to centralized power stations at comparable investment and operational costs (Dasappa et al. 2005, Ravindranath et al., 2000; Ravindranath et al., 2006). These aspects of performance are *rarely matched* by other renewable resources like solar, wind and hydro. Yet the degree of understanding of the efficient use of biomass-derived fuels like producer gas and biogas for various purposes is *perhaps the least* among all renewables. There has been very little effort to develop the use of bioenergy for small capacity (say less than 1 MW) electricity generation, especially for distributed generation.

This paper addresses the existing energy scenario in Africa and the possible alternatives using biomass to meet the electricity demand, especially for off-grid solutions. The paper consolidates information from various studies on the availability of different bio-resources and estimates possible power potential that can be realized. Experience in generating electricity using biomass gasification technology in the distributed generation mode from other developing countries is also highlighted. The paper provides simple economic analysis of power generation using biomass gasification. The paper also highlights the need to address the barriers to developing biomass based power generation as an important intervention.

## Electrical energy consumption pattern in Africa

Energy consumption in Africa (UNECA, 2006) is largely dominated by biomass amounting to more than 80% in some countries, such as Burundi (91%), Rwanda and the Central African Republic (90%), Mozambique (89%), Burkina Faso (87%), Benin (86%), Madagascar and Niger (85%) (UNECA, 2006). Biomass is used as the main energy resource for the majority of African households for cooking, drying and space heating. Several million people are involved in the production, distribution and sale of fuel wood and charcoal. Energy in Africa is produced mainly from biomass (47%), oil (24.8%), coal (16.5%), gas (10.4%), and other renewable sources, such as large and small hydro, solar, and geothermal sources (1.3%) (Benoit, 2006).

### *Electrical energy scenario in Africa*

The African continent, which accounts for 13% of the world's population, generates about 3.1% of the world's electricity. Many countries in sub-Saharan Africa depend on hydropower for electricity generation, one exception being South Africa (OECD, 2009). The per capita annual electricity utilization was about 515 kWh (WEC, 2002), probably the lowest of any major region in the world. Access to electricity ranges from greater than 90% in northern Africa to about 26% in SSA and to less than 1% in the rural areas of SSA (IEA, 2009).

The very limited availability of electricity, combined with issues of affordability of electricity services in most countries, has blocked access to electricity by most Africans. While electricity access data varies widely depending on the reporting sources, the summary of data from various sources for 2005 was compiled in IEA (2006a,b) and is presented in Table 1. From Table 1 it is clear that the population in the sub-Saharan region has extremely low access to electricity compared with the population in North Africa. On the basis of this data 62% of Africa's population – equivalent to more than 360 million people – has no access to electricity. Except for South Africa, and Ghana, and the islands of Mauritius and Seychelles none of the SSA countries exceed 50% access to electricity and in about half of the African countries, it is under 25%. In more than 10 countries, less than 10% of the population has access to electricity. While 52% of the urban population in sub-Saharan Africa has access, it is as low as 8% in rural areas. These numbers do not reflect the large disparities that exist across countries (for instance less than 4% in Uganda compared to 66% in South Africa or 100% in Mauritius) (WEC, 2002). In countries like Congo, Mozambique, Burkina Faso, Malawi, Uganda, Lesotho and Tanzania, less than 10% of the population has access to electricity.

Table 2 indicates electricity generation for a few countries in Africa and the total *(IEA, 2006a,b)*. From Table 2 it is clear that South Africa generates about 40% of the total generated in the continent. Between them, Algeria, Egypt and South Africa generate about 68% of the total electricity and electricity access for the population in these countries is 98%, 98% and 65% respectively.

Cogeneration in the sugar industry is an important part of the biomass sector which is gaining importance in Africa, but currently accounting for only about 15% of the overall potential. Mauritius is an excellent example, generating about 40% of its total power from sugar cane cogeneration.

Table 1 also shows the disparity that exists in the northern and southern regions of Africa with regard to electricity access, with 26% of the population having electricity in the SSA region compared with 95% access in the north.

Analyzing the present situation with respect to access to electricity and considering the prevailing power sector reforms in the region, it is evident that centralized power generation will not be able to meet the universally accepted Millennium Development Goals (MDGs) (Modi et al. (2005). It is now widely recognized that renewable, especially

**Table 1**
Electricity access in Africa in 2005.

| Country | Electrification rate (%) | Population without electricity (million) | Population with electricity (million) |
|---|---|---|---|
| Angola | 15 | 13.5 | 2.4 |
| Benin | 22 | 6.5 | 1.8 |
| Botswana | 38.5 | 1.1 | 0.7 |
| Burkina Faso | 7 | 12.4 | 0.9 |
| Cameroon | 47 | 8.7 | 7.7 |
| Congo | 19.5 | 3.2 | 0.8 |
| Dm. Rep. Congo | 5.8 | 53.8 | 3.3 |
| Cote D'Ivoire | 50 | 9.1 | 9.1 |
| Eritrea | 20.2 | 3.5 | 0.9 |
| Ethiopia | 15 | 60.8 | 10.7 |
| Gabon | 47.9 | 0.7 | 0.7 |
| Ghana | 49.2 | 11.3 | 10.9 |
| Kenya | 14 | 29.4 | 4.8 |
| Lesotho | 11 | 1.9 | 0.2 |
| Madagascar | 15 | 15.2 | 2.7 |
| Malawi | 7 | 11.8 | 0.9 |
| Mauritius | 93.6 | 0.1 | 1.2 |
| Mozambique | 6.3 | 18.6 | 1.3 |
| Namibia | 34 | 1.4 | 0.7 |
| Nigeria | 46 | 71.1 | 60.5 |
| Senegal | 33 | 7.8 | 3.8 |
| S. Africa | 70 | 14 | 32.6 |
| Sudan | 30 | 25.4 | 10.9 |
| Tanzania | 11 | 34.2 | 4.2 |
| Togo | 17 | 5.1 | 1 |
| Uganda | 8.9 | 24.6 | 2.4 |
| Zambia | 19 | 9.5 | 2.2 |
| Zimbabwe | 34 | 8.7 | 4.5 |
| Other countries | 7.6 | 83.6 | 6.9 |
| **Sub-Saharan Africa** | **25.9** | **546.9** | **190.7** |
| Algeria | 98.1 | 0.6 | 32.3 |
| Egypt | 98 | 1.5 | 72.4 |
| Libya | 97 | 0.2 | 5.7 |
| Morocco | 85.1 | 4.5 | 25.8 |
| Tunisia | 98.9 | 0.1 | 10 |
| **North Africa** | **95.5** | **6.9** | **146.1** |
| **Africa** | **37.8** | **553.7** | **336.8** |

The bold characters in the table are only to highlight the key figures. In some cases they provide the overall data for a given region.
(Source: World Energy Outlook 2006, Annex B, Electricity Access (IEA, 2006).

**Table 2**
Electricity generation for 2006 in different parts of Africa.

| Country | Electricity generation (Terawatt hrs) |
|---|---|
| Algeria | 35.0 |
| Egypt | 110.7 |
| South Africa | 258.5 |
| Other Africa | 191.8 |
| **Total Africa** | **596.0** |

The bold characters in the table are only to highlight the key figures. In some cases they provide the overall data for a given region.
(Source: http://www.bp.com).

off-grid, solutions, could play an important role in reducing the access gap, in remote rural areas (Reddy, 1999) and be relevant to some urban areas too as captive power generation systems to have reliable source of energy supply.

It must be stated that access to electricity using decentralized power generation is not merely providing illumination, but has to provide livelihood opportunities depending upon the region. Typical examples that can be cited where productive operations depend on electricity are: agriculture when it depends on water pumping, perishable products like vegetables, fruits, and fish, by providing either cold storage or ensuring heat for dehydration for agricultural products, etc. Such use of electricity will enhance the shelf life of agricultural produce and fetch it appropriate economic returns.

## An overview of biomass resource in the region

Benoit (2006) and Karekezi and Kithyoma (2003) highlight that biomass is one of the largest renewable energy resources in the SSA region. In the context of this paper, biomass resource refers to residues from forests, agro residues and any other wastes generated during the processing of industrial wood products. Kauffmann (2005) summarizes usage and access to biomass in the sub-Saharan region and compares this data with that for other regions of the world. According to his analysis, about 90% people in sub-Saharan Africa use biomass, such as wood or residues, for cooking and heating and 60% of African women living in rural areas have to deal with the scarcity of supply of firewood.

Batidzirai et al. (2006) study the possible role of biomass fuel production in Mozambique. The authors estimate that Mozambique could produce up to 6.7 EJ of bioenergy annually with structured agricultural technology practices and respecting importantly the issue of food versus energy sustainability. Comparing the various technologies and production regions, it establishes the conditions and critical factors for a successful bioenergy program in Mozambique. This estimate seems to be very high.

Davidson and Mwakasonda (2004)summarize the use of various fuels for energy purposes in Zimbabwe. It is clear that at the national level, access to biomass and charcoal varies from 78% in the urban areas to 98% for the rural areas meaning significant population depend on biomass based fuel.

Further, an estimate of 380 kg of oil equivalent is used per capita for cooking using fuel wood (Amous, 1999). Assuming nearly 600 million people depend on biomass as a source of cooking in Africa and energy equivalent of 0.89 $m^3$ per capita per year (Amous, 1999). These estimates suggest that about 530 million $m^3$ of wood equivalent of energy is required for cooking. From Table 4b, adding the amount of wood fuel and an equivalent wood converted for charcoal sum up to 513 million $m^3$ which of the same order as the above estimates. Appendix 1 provides the details.

Another source on the availability of biomass resource for energy purpose is the non-valued residues from non-edible oil extraction. Currently considerable activity on the development of biodiesel is concentrated in the African region. It must be noted that the oil is a small fraction of the seed used for the extraction. The residue from oil extraction is significant in quantity and would be available for other uses. Some of these contemplated uses are as food like soy meal, fertilizer, pesticide, etc., while most of it is available as fuel due to the toxic nature of the cake generated as in the case of Jatropha. Apart from the seed, there are other plant residues which are lignin based that need attention to disposal and handling.

### *Forest resource base*

Analyzing the data from FAO (2005), Africa has about 650 million hectares (Mha) of land covered by forests and this corresponds to 17% of the world's total forest area. The forest cover is about one-fifth of the continent's land area, and unevenly distributed, with the Congo basin accounting for the largest share. In the forest-rich countries of West and Central Africa, production of industrial roundwood and wood products is a major source of employment. It is interesting to observe that African forests amount to 0.85 ha per capita of population, and this value is close to the world average. Africa has about one-quarter of all tropical rain forests. Only 1% of the forest area in Africa is classified as forest plantations.

Tables 3a and 3b synthesize the data on the forest products from FAO (2005). Table 3asummarizes the total land area under forests and other wooded land in the region. The total land area is about 3000 Mha in the region and about 645 Mha amounting to 21% of the land area has biomass cover. The last column in Table 4a is the total sum of forest area, wooded, other land and inland water.

From Table 3a it is clear that the northern region has a small fraction of forest land compared to the other regions. Of the total land area of 650 Mha, about 280 Mha is covered with forest in Western and Central Africa, which amounts to about 44%. For the northern region it is about 8.6%, and 28% for Eastern and Southern Africa. While the forest cover is low in the Northern region, fossil fuel resources are high there compared to in the other regions. It is in the other regions that one needs to address solutions using biomass-derived fuels in the energy matrix. On the basis of the biomass availability data in the

**Table 3a**
Forest and wooded land in 2005.

| Country/area | Land area | | | | | Inland water | Total area |
|---|---|---|---|---|---|---|---|
| | Forest | | Other wooded land | Other land | | | |
| | | | | Total | With tree cover | | |
| | 1000 ha | Land area (%) | 1000 ha | 1000 ha | 1000 ha | 1000 ha | 1000 ha |
| Eastern and Southern Africa | 226,534 | 27.8 | 167,023 | 421,024 | 10,345 | 19,799 | 834,380 |
| Northern Africa | 131,048 | 8.6 | 94,609 | 1,297,696 | 10,207 | 26,464 | 1,549,817 |
| Western and Central Africa | 277,829 | 44.1 | 144,468 | 208,227 | 788 | 16,253 | 646,776 |
| **Total Africa** | **635,412** | **21.4** | **406,100** | **1,926,946** | **21,339** | **62,516** | **3,030,974** |

The bold characters in the table are only to highlight the key figures. In some cases they provide the overall data for a given region.
(Source: http://www.fao.org/).

**Table 3b**
Forest products for some countries.

| Countries | Industrial round wood | Pulpwood, round and split | Round wood | Log: saw & veneer | Sawn wood | Wood fuel | Wood-based panels | Paper & paper board | Wood charcoal | Wood pulp |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1000 $m^3$ | | | | | | | 1000 tons | | |
| Benin | 332 | | 494 | 35 | 31 | 162 | | 0 | 205 | 0 |
| Botswana | 105 | | 760 | | | 655 | | 0 | 65 | |
| Congo | 3653 | | 73430 | 170 | 40 | 69777 | 3 | 3 | 1646 | |
| Egypt | 268 | | 17060 | 134 | 2 | 16792 | 56 | 460 | 1265 | |
| Ethiopia | 2928 | 7 | 95957 | 4 | 18 | 93029 | 93 | 16 | 3221 | |
| Gabon | 3500 | | 4570 | 3500 | 133 | 1070 | 222 | 0 | 17 | 0 |
| Ghana | 1350 | | 22028 | 1350 | 480 | 20678 | 435 | 0 | 752 | 0 |
| Kenya | 1792 | 391 | 22162 | 241 | 78 | 20370 | 83 | 165 | 18 | 98 |
| Libya | 116 | | 652 | 63 | 31 | 536 | | 6 | | |
| Malawi | 520 | | 5622 | 130 | 45 | 5102 | 18 | 0 | 426 | 0 |
| Mozambique | 1319 | | 18043 | 128 | 28 | 16724 | 3 | 0 | 100 | |
| Niger | 411 | | 9007 | | 4 | 8596 | | 0 | 483 | 0 |
| Nigeria | 9418 | 39 | 70270 | 7100 | 2000 | 60852 | 95 | 19 | 3421 | 23 |
| South Africa | 21159 | 14833 | 33159 | 5236 | 2171 | 12000 | 1022 | 3774 | 201 | 2076 |
| Sudan | 2173 | | 19655 | 123 | 51 | 17482 | 2 | 3 | 850 | |
| Swaziland | 330 | 0 | 890 | 260 | 102 | 560 | 8 | | | 191 |
| Tanzania | 2314 | 153 | 23819 | 317 | 24 | 21505 | 4 | 25 | 1328 | 54 |
| Uganda | 3175 | | 39410 | 1055 | 264 | 36235 | 5 | 3 | 792 | |
| Zambia | 834 | | 8053 | 319 | 157 | 7219 | 18 | 4 | 1041 | |
| Zimbabwe | 992 | 94 | 9108 | 786 | 397 | 8115 | 77 | 80 | 9 | 42 |
| Total | 56689 | 15517 | 474149 | 20951 | 6056 | 417459 | 2144 | 4558 | 15840 | 2484 |

southern region, biomass based sustainable energy solutions are possible; using distributed power generation.

Table 3b provides details on the forest based produce. Considering mainly the industrial products, fuel wood and charcoal, it is evident that the major product is the round wood production amounting to about 474 million $m^3$ while the fuel wood is about 417 million $m^3$. At a density of about 500 kg/$m^3$, these figures would translate to about 237 million tons and 207 million tons of round wood and fuel wood respectively. Charcoal production is about 15 million tons. Fuel wood used to generate charcoal amounts to about 52 million tons at a typical conversion factor of 30% from wood to charcoal. The amount of wood for charcoal generation is about 25% fuel wood production.

### *Fraction of woody biomass used for energy*

Table 4 (FAO, 2005) reports the ratio of wood fuel production to the total industrial roundwood production in Africa. On an average, the ratio for 2000 was estimated at 0.94, meaning for every ton of total industrial roundwood produced, 0.94 ton of fuel wood is also produced. This is evident from Table 3b comparing column on round wood and wood fuel the ratio is about 0.9. On the basis of the ratio, it is clear that fuel wood production is comparable to industrial round wood production. Further considering industrial wood production as a bio-resource, it is important to recognize that during processing, wastes generated, like off-cuts, sawdust, lops and tops, are available as residues. With the area under the forest and non-forest zones amounting to about 1000 Mha and even with a modest yield of 1.0 to 2 tons of wood per ha per year which is in the range of mean fuel wood production was estimated at 1.93 $m^3$ $ha^{-1}$ $year^{-1}$ (Amous, 1999). The amount of residue available from the existing operation would be equivalent of 1000 million tons (Mt) annually. Apart from the waste generated from the existing forest area, wastelands can also be used for the purpose of biomass generation.

**Table 4**
Fraction of wood fuel production in total round wood production at year 2000.

| Country | Wood fuel/total round wood |
|---|---|
| Burundi | 0.94 |
| Democratic Republic of Congo | 0.95 |
| Egypt | 0.98 |
| Eritrea | 1.00 |
| Kenya | 0.91 |
| Rwanda | 0.93 |
| Somalia | 0.99 |
| Sudan | 0.88 |
| Tanzania | 0.90 |
| Uganda | 0.91 |
| **Average** | **0.94** |

The bold characters in the table are only to highlight the key figures. In some cases they provide the overall data for a given region.
(*Source:* FAO 2005).

### *Agricultural residue*

Typically the ratio of crop to residues that are generated during cereal production and processing, defined as the CR ratio or CRR (crop to residue ratio), can be in the range of 0.2 and 3.0 for the husk and about 3.0 for the stalk, respectively as is presented in Table 5 (CGPL, 2011). With the total cereal production at about 140 Mt, and assuming a modest CRR of 1.0 for the entire agro production, the contribution of residues to the biomass potential is about 140 Mt of stalks and husk. Table 6

**Table 5**
Crop to residue ratio (CRR) for various agricultural products (CGPL, 2011).

| Crop | Residue | CRR | Crop | Residue | CRR |
|---|---|---|---|---|---|
| Barley | Stalks | 1.30 | Paddy | Straw | 1.50 |
| Bar seem | Stalks | 1.00 | Paddy | Husk | 0.20 |
| Black pepper | Stalks | 0.50 | Paddy | Stalks | 1.50 |
| Gram | Stalks | 1.15 | Peas & beans | Stalks | 0.50 |
| Groundnut | Stalks | 2.00 | Potato | Leaves | 0.76 |
| Groundnut | Shell | 0.30 | Potato | Stalks | 0.05 |
| Guar | Stalks | 2.00 | Pulses | Stalks | 1.30 |
| Horse gram | Stalks | 1.30 | Safflower | Stalks | 3.00 |
| Jowar | Cobs | 0.50 | Sannhamp | Stalks | 2.52 |
| Jowar | Stalks | 1.70 | Sawan | Stalks | 1.00 |
| Jowar | Husk | 0.20 | Small millets | Stalks | 1.20 |
| Kodo millets | Stalks | 1.16 | Soyabean | Stalks | 1.70 |
| Linseed | Stalks | 1.47 | Sugarcane | Tops & leaves | 0.05 |
| Maize | Stalks | 2.00 | Sunflower | Stalks | 2.00 |
| Maize | Cobs | 0.30 | Sweet potato | Stalks | 0.10 |
| Mustard | Stalks | 1.80 | Tapioca | Stalks | 0.72 |
| Mustard | Husk | 0.43 | Tea | Sticks | 1.00 |
| Niger seed | Stalks | 1.07 | Tobacco | Stalks | 1.00 |
| Oilseeds | Stalks | 2.00 | Wheat | Stalks | 1.50 |
| Onion | Stalks | 0.05 | Wheat | Pod | 0.30 |

Box 1
Case study for village electrification — mini grid.

Major activity was carried out at the Indian Institute of Science towards meeting the unmet demand of electricity in the year 1988 at Hosahalli (Ravindranath et al., 2004; Somashekhar et al., 2000; Srinivas et al., 1992). Hosahalli, previously an unelectrified 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 rain-fed 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 the addition of other services like flour milling and irrigation water requirements as well. The total connected load, comprising 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 the 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 improved quality of life, such as home and 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 what was available from 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 and water, should be provided by the government, along with some groups with vested interests within the village wanting 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 as was available through the gasifier based power system. There were frequent power outages — a feature existing in most rural grids in India. Further, the gasifier-based project was addressing services like water and illumination, and not merely electricity.

provides the detailed data of cereal production in Africa. Each of the top four cereal producing countries (Egypt, Ethiopia, Nigeria and South Africa) cross 10 million tons (Mt) of cereal production per year and about 24 countries produce cereals in the range of 1 to 10 Mt (FAO, 2005).

## Choice of technology

Having identified biomass as a potential resource for power generation, the choice of the technology for implementation is an important factor. Biological and thermo-chemical conversion technologies are available for utilizing biomass to generate a fuel gas — biogas and producer gas respectively. The fuel gas can be used either for thermal energy or power generation. Generally, biological conversion is a preferred option for moist raw material with high cellulosic content and thermo-chemical conversion is preferred for a wide range of biomass including high ligno-cellulosic content. The biomass feedstock considered in this paper (wood and agricultural residue) is basically dry, hence the thermo-chemical path using gasification is more appropriate and discussed below.

Box 2
Case study for village electrification with grid connection (Dasappa et al., 2011).

The ongoing operational experience from a 100 kWe gasification power plant connected to the grid in Karnataka. Biomass Energy for Rural India, a program under Government of Karnataka/UNDP/MNRE, implemented gasification based power generation with an installed capacity of 0.88 MWe distributed over 3 locations to meet the electrical energy needs in the district of Tumkur apart from other energy initiatives.

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 a turbo-charged engine. The producer gas is used as a fuel in a Cummins India Limited, GTA 855 G model, turbo-charged engine and the power output from the alternator is connected to the grid.

The system has operated for over 1000 continuous hours, with only about 70 h of grid disturbance. The total biomass consumption for 1035 h of operation is 111 tons at an average 107 kg/hr. Total energy generated is 80.6 MWh saving over 100 tons of $CO_2$. The overall specific fuel consumption is about 1.36 kg/kWh, amounting to an overall biomass-to-electricity conversion efficiency of about 18%. The present operations have shown that a maintenance schedule for the plant can be at the end of 1000 h.

Fig. 1 presents the performance of various thermo-chemical conversion technologies that are possible using biomass as a fuel. The plot presents the variation of power with conversion efficiency for various technological options (Ralph, 1998). The conventional usage of biomass in the power sector has been for generating steam and using a steam turbine. The efficiency of a steam based power plant is low at power levels below 5 MW and hence the specific fuel consumption can be high. It is also important to highlight that at power levels in excess of 5 MW the techno-economics are favorable. The other option available at high power levels is the integrated gasification combined cycle, where efficiency in excess of 40% is possible. It is evident that even at low power levels, in the range of less than 200 kW, gasification based power generation using an internal combustion engine provides better efficiency for biomass utilization. The other options of using gasification are fuel cells and gas turbines which are in various stages of development for commercial applications.

Considering the wide range of requirements both for power generation systems in the SSA, it is argued that biomass gasification is one of the more promising options for Africa.

### *Gasification overview*

Solar energy captured by photosynthesis and stored in the biomass makes it a high-energy density system (16 MJ/kg). Gasification of this fuel is partial combustion of biomass to produce gas and char at the first stage and subsequent reduction of the product gasses, chiefly carbon dioxide ($CO_2$) and water ($H_2O$), by the charcoal into carbon monoxide (CO) and hydrogen ($H_2$). The process also generates

**Table 6**
Agro residues and power generation potential in Africa (*Source:*http://www.fao.org/).

| Country | Cereal production in million tons | Agricultural residues in million tons* | Power potential at 30% availability, MW |
|---|---|---|---|
| Algeria | 3.998 | 3.998 | 150 |
| Angola | 0.725 | 0.725 | 27 |
| Benin | 1.109 | 1.109 | 42 |
| Botswana | 0.045 | 0.045 | 2 |
| Burkina Faso | 2.902 | 2.902 | 109 |
| Burundi | 0.280 | 0.280 | 11 |
| Cameroon | 1.684 | 1.684 | 63 |
| Cape Verde | 0.004 | 0.004 | 0 |
| Central African Republic | 0.192 | 0.192 | 7 |
| Chad | 1.213 | 1.213 | 45 |
| Comoros | 0.021 | 0.021 | 1 |
| Democratic Rep of Congo | 1.570 | 1.570 | 59 |
| Côte d'Ivoire | 2.205 | 2.205 | 83 |
| Egypt | 21.315 | 21.315 | 799 |
| Eritrea | 0.083 | 0.083 | 3 |
| Ethiopia | 9.280 | 9.280 | 348 |
| Gabon | 0.032 | 0.032 | 1 |
| Gambia | 0.213 | 0.213 | 8 |
| Ghana | 1.943 | 1.943 | 73 |
| Guinea | 1.142 | 1.142 | 43 |
| Guinea-Bissau | 0.171 | 0.171 | 6 |
| Kenya | 2.730 | 2.730 | 102 |
| Lesotho | 0.248 | 0.248 | 9 |
| Liberia | 0.110 | 0.110 | 4 |
| Country | Cereal production in million tons* | Agricultural residues in million tons | Power potential at 30% availability, MW |
| Libya | 0.213 | 0.213 | 8 |
| Madagascar | 3.391 | 3.391 | 127 |
| Malawi | 1.843 | 1.843 | 69 |
| Mali | 2.845 | 2.845 | 107 |
| Malta | 0.012 | 0.012 | 0 |
| Mauritania | 0.125 | 0.125 | 5 |
| Morocco | 8.604 | 8.604 | 323 |
| Mozambique | 2.007 | 2.007 | 75 |
| Namibia | 0.107 | 0.107 | 4 |
| Niger | 2.672 | 2.672 | 100 |
| Nigeria | 22.783 | 22.783 | 854 |
| Rwanda | 0.319 | 0.319 | 12 |
| Senegal | 1.085 | 1.085 | 41 |
| Sierra Leone | 0.309 | 0.309 | 12 |
| South Africa | 12.352 | 12.352 | 463 |
| Sudan | 3.643 | 3.643 | 137 |
| Swaziland | 0.071 | 0.071 | 3 |
| Tanzania | 5.020 | 5.020 | 188 |
| Togo | 0.787 | 0.787 | 30 |
| Tunisia | 2.155 | 2.155 | 81 |
| Uganda | 2.625 | 2.625 | 98 |
| Zambia | 1.364 | 1.364 | 51 |
| Zimbabwe | 0.837 | 0.837 | 31 |

*The agricultural residues are estimated at crop to residue ratio.

methane and other higher hydrocarbons depending on the design and operating conditions of the reactor. The development of the technology to harness this route has taken place in spurts. The energy value of producer gas is about 5.0 MJ/m$^3$. (Kaupp and Goss, 1984; Reed and Jantzen, 1979).

The combustible producer gas can be used in internal combustion engines in one of two ways. It can be used in a diesel engine together with a small fraction of diesel (Dasappa et al., 1989, 2004; Ghosh et al., 2004; Jain, 2000; Ravindranath et al., 2004). This is called dual-fuel operation. Diesel saving up to 80% is possible while operating with producer gas (Ravindranath et al., 2004). In the dual-fuel mode, gas and air mixture is drawn into the engine cylinder and the amount of diesel is regulated by the governor fitted on the engine to maintain the electrical frequency at a given load.

Producer gas by itself can also be used in a spark ignited engine (ABETS, 2003; Dasappa et al., 2011; Knoef, 2005; Sridhar et al., 2005).

Biomass gasification technology has proved to be an efficient way of using biomass at power levels in the range of a few kW to about 2 MW capacity (Fig. 1). Attempts have been made to meet combined heat and power (CHP) requirements using the reciprocating engine route for power generation. These have been possible using circulating fluidized bed gasification technologies with steam or air as the reactive medium. Fixed bed-updraft technologies using catalytic tar reforming and staged gasification technology to improve the carbon conversion have also been implemented. These fuel conversion devices are identified as better technology packages for small-scale power generation compared to direct combustion, on the basis of the existing data from the literature (Knoef, 2005). Usage of CHP can help improve overall efficiency in situations where apart from electricity, there is a potential demand for heat in the form of either hot fluid or refrigeration (using absorption cooling).

It may be appropriate to mention that biomass gasification technology would meet objectives like using local feedstock to provide reliable grid quality electricity to meet the energy demand for both the rural as well as the urban sector. On the basis of these potentials and reserves, biomass gasification can also contribute toward providing a well-balanced energy generation mix on the continent. Biomass gasification technology is an option to replace/substitute existing oil

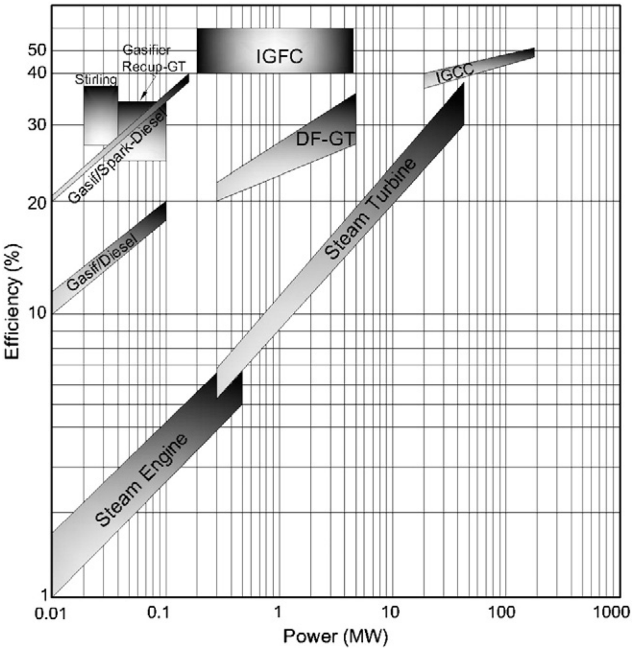

**Fig. 1.** Performance of various thermo-chemical conversion technologies (Ralph, 1998) (IGFC — Integrated gasification and Fuel Cell ,IGCC — Integrated gasification and combined cycle, DFGT — Dual fluid gas turbine).

based electricity generation in remote locations. It is also important to recognize that this modern bio-energy technology is a promising candidate for mitigating climate change, insofar as it would offset kerosene used for lighting and diesel used for power generation.

### *Experience of gasification technology in India*

India has shown leadership in biomass gasification technology. The (national) Ministry of New and Renewable Energy Sources (MNRE) has played a key role in India, in both R and D and implementation (MNRE, 2010). There are critically about 5 groups involved both in the development and in implementation of the technology package, directly or using a licensing mechanism. The technology packages developed between these groups are different. M/s ASCENT have developed packages for woody biomass, fine biomass and a combination of the two (Ankur, 2010; Jain, 1995). A closed top gasification system has been used for the conversion process. A rice husk gasification system is designed separately to handle rice husk as received. The research group at The Energy and Resources Institute (TERI) has developed technology packages for woody and briquetted biomass using a throatless gasifier with closed top (TERI, 2009). Sardar Patel Renewable Energy Research Institute (SPRERI) has been involved in the development of technology packages for dual fuel and thermal applications, using both forced and natural draft depending upon the requirements (SPRERI, 2009). The Indian Institute of Science has developed a multi-fuel gasification system to accept woody or biomass briquettes (CGPL, 2011).

Significant progress has been made in India and particularly at the Indian Institute of Science (IISc), Bangalore, in the development and commercialization of this technology. Technology packages using biomass as fuels have been developed to meet electricity demand (CGPL, 2011). Using gas engines, electricity can be generated at a specific fuel consumption of 1.0–1.2 kg/kWh. This modern bioenergy technology is also an important component of the mitigation options for climate change (Ravindranath et al., 2006). There are many examples in the literature of achieving economical solutions with electrical conversion efficiencies in the range of 25–30% at small capacity power plants (~1000 kWe) using downdraft gasifiers (Dasappa et al., 2007; Knoef, 2005; Sridhar et al., 2005).

Post 2000 there has been activity toward developing reliable industrial technology packages for both power generation and thermal application in India. In the power generation sector the emphasis shifted from dual fuel to pure gas engine mode, in order to compete with the grid costs with increase in fossil fuel prices. Gas engines to accept producer gas as a fuel were not commercially available and some research groups carried out the R and D to operate engines on producer gas. While various groups developed skills to adapt natural gas engines to operate on producer gas, the Indian Institute of Science, working with Cummins India Limited (CIL), has been able to develop a package for a producer gas engine. The research group has built the largest capacity power plant connected to the grid using gas engines supplied by Cummins India Limited. Currently, CIL would be the first engine manufacturer to produce engines to accept producer gas as a fuel in India. Power generation using engines up to 2 MWe and 10 MWth have been developed and deployed in the field.

Boxes 1 and 2 cite examples of some of the biomass based power generation systems used for rural communities.

### *Overall power generation potential in the SSA using biomass*

Table 7 summaries various biomass resources available in the region based on the data presented earlier in the paper. Column A identifies different biomass resources in the region. Columns B and C represent the area under production and biomass generation. Column F shows estimated biomass available for power generation and Column G provides the power generation. In estimating forest area, only additional area is taken into account, with the usage of the land for the fuel wood and industrial wood.

**Table 7**
Summary of biomass potential for power generation.

| A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| Biomass resource as | Total land under wood m ha | Biomass generation m $m^3$ | Total | Requirement | Assumed available for power generation, million tones | Power generation potential, MW |
| Fuel wood | 216 | 417 | 522 | 523 | 0 | 0 |
| Charcoal | 55 | 105 | | | | |
| Industrial wood | 297 | 583 | 603 | | 90.4[a] | 11297 |
| Industrial wood | 9.5 | 19.5 | | | | |
| Crop residue | 70 | 140 | 98 | | 42[b] | 4286 |
| Forest area in south, west and central Africa | 248 | 478 | | | 24[c] | 2992 |
| Total | | | | | 198 | 18574 |

[a] Assumed that 30% of industrial wood process waste like, saw dust, off cuts, will be available for power production.
[b] Assumed that 30% of the residues from the crop production as husk, stalks, will be available for power production.
[c] Assumed that 10% of the forest produce as off cuts, branches, will be available for power production.

It is also assumed that there are no residues available from the biomass generated for fuel wood and charcoal manufacturing and hence the Column F identifies it as zero. In estimating the agro residues as mentioned earlier based on the CRR, the residues are estimated.

In arriving at the power potential, an overall efficiency of about 20% for power plants less than 50 kW and greater than 25% for power range between 50 and 250 kW and closer to 30% for power plants greater than 250 kW is assumed (Dasappa et al., 2007, 2011). It is also assumed about 80% overall plant load factor in estimating the power potential.

It must be emphasized that the power generation potential projection is arrived at on the basis of the currently available residues, without taking into account any dedicated plantation using wasteland.

Table 6 also provides details of the power potential in different countries on the basis of the above assumption. It is evident that Nigeria, South Africa, Morocco, Tanzania, Sudan, Madagascar, Niger, Mali, Uganda, Egypt, Ethiopia, Algeria, Burkina Faso and Kenya account for a generation potential of about 4000 MW. From Table 2, of the 460 TWh generated during 2006 in the sub-Saharan region, South Africa contributes about 260 TWh. Table 7 consolidates the currently available biomass in and it is estimated only a small fraction can be assumed to be surplus for power generation.

On the basis of the biomass available in SSA and assuming a small fraction (~30% availability) of residues is available from the forests and agriculture production, the possible power potential is about 15,000 to 20,000 MW. With a conservative estimate of the biomass residues available as indicated above, potential to generate about 100 TWh a year of electricity exists, and this amounts to more than 25% of the present (2006) generation in the SSA region and nearly 50% excluding South Africa.

## Gasification programs in Africa

Biomass as a source of generating electricity has not been extensively explored in the African region except in South Africa. There have been attempts in recent times by different countries in the region to establish demonstration projects. An example of this is the recent effort by the Ministry of Energy and Mineral Development, Uganda, for a gasification system package being implemented to meet heat and power requirements of small capacity (World Bank, 2009). There have been many attempts by some gasification development groups to establish programs in African countries for demonstration projects, but these have not made any significant impact.

Carbo Consult and Engineering (Pvt) Ltd has established a gasification technology – System Johansson Gas Producers – in South Africa. From the available information (CCEL, 2009), the company has a few installations in South Africa and has been interacting with other countries outside the region for commercial opportunities. The technology package is to operate on dual fuel mode as well in the gas alone mode. There are very few systems in the region.

### *Case studies of biomass gasification in the region*

Hammond and Kemausuor (2008) summarize the experience of using gasifiers in Africa. In Uganda a 10 kW system was supplied (2007) by an Indian company, Ankur Scientific, to operate on dual fuel mode. A minigrid was connected to a farmhouse, pigsty 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/kWh of wood and 0.17 liters/kWh of diesel. A simple analysis of this data would show about 60% diesel substitution. A few other systems are deployed at slightly higher capacities where no published documentation is available. Another operation dating back to the 1960s is based on rice husk gasification in Mali in cooperation with a Chinese group. In Burundi, a dual-fuel system for about 36 kW under a European program was supplied from Belgium. The system has not operated for a long time. Hammond and Kemausuor also make an important statement that the criteria for gasifier selection should include feedstocks, manpower, spare parts and environmental conditions to meet the local conditions rather than the available global choice.

### *Techno-economics*

Diesel based power generation is widely sought option to service the rural community if grid electricity is not available in the region. This option has ensured that bare minimum electricity provided by the utility — mostly illumination and other critical loads. With the existing cost of diesel at 1.25 USD per liter across most of the SSA countries, the fuel cost component of diesel-based electricity is about 30 cents (US) per kWh excluding the labor and maintenance cost. With average cost of electricity charged to the customers in the range of 5 cents (US) per kWh (Anon, 2011; Kenya, 2011; Nersa, 2011), there is a substantial subsidy. Table 8 provides a simple economic comparison of operating two gasification systems with diesel based power generation, on the basis of annualized lifecycle cost (ALC) (Sadhan et al., 2009). Capital costs used in the calculation are presented in Table 8. Further, it must be stated that cost per kW chosen also depend upon the capacity of the system. For lower capacity below 100 kW capacity the cost indicated in the table is applicable, while at larger capacity, the cost can be lower depending upon the power plant requirements. It must be said that fuel consumption assumed is on an average for a range of power levels. Comparison of fuel cost per kWh based on specific energy consumption in the dual fuel and gas alone operations reveals biomass energy generation is economical. Table 8 provides the assumptions made in the analysis. The operation and maintenance cost is for the diesel engine power generation is at 4 US cents per kWh and an additional cost of 3 US cents per kWh with gasification. The diesel based power generation is about 50 USc per kWh against the gasifier based power generation which is about 18 USc per kWh. There is a clear savings of about 32 cents (US) per kWh.

## Key barriers and issues for biomass gasification

With the exception of a few oil-producing countries such as Angola, Cameroon, Egypt, Equatorial Guinea, Libya, Nigeria and Tunisia, most

**Table 8**
Simple economics of gasifier operation.

| | Diesel operation | Dual fuel (70% replacement) | Gas engine |
|---|---|---|---|
| Biomass gasification system cost (excluding the engine) ($/kW) | Nil | 900 | 900 |
| Engine cost ($/kW) | 300 | 300 | 700 |
| Project life (yr) | 15 | 15 | 15 |
| Engine life (yr) | 7.5 | 7.5 | 7.5 |
| Discount rate | 10 | 10 | 10 |
| Diesel cost ($/liter)[a] | 1.25 | 1.25 | Nil |
| Biomass cost ($/ton) | Nil | 50 | 50 |
| O&M cost ($/kWh) | 0.04 | 0.07 | 0.07 |
| Fuel consumption (kg/kWh) | Diesel : 0.272 | Biomass : 0.9<br>Diesel : 0.082 | Biomass : 1.1 |
| SFC (MJ/kWh)<br>Biomass: 16 MJ/kg; Diesel: 42 MJ/kg | 11.4 | 17.8 | 17.6 |
| Plant load factor (%) | 75 | 75 | 75 |
| Annual Fuel cost ($) | 2628 | 544 | 329 |
| Annual O &M cost ($) | 292.0 | 306.6 | 438 |
| Cost recovery of gasifier ($) | Nil | 118 | 118 |
| Cost recovery factor for engine ($) | 58.74 | 58.74 | 137.06 |
| Annualized total lifecycle cost ($) | 2979 | 1028 | 1022 |
| Annual energy generation (kWh)[b] | 6570 | 6570 | 6570 |
| Annualized lifecycle cost of energy ($/kWh) | 0.50 | 0.184 | 0.183 |

[a] Diesel cost ($/kWh) = (Diesel consumption (kg/kWh) /density of diesel (kg/liter)) x Diesel cost ($/liter) = ( 0.272/0.85)*1.25 = 0.4.

[b] Gasification system 15% in house consumption.

African countries import petroleum in the form of either crude oil or its refined products. In these countries, petroleum imports can account for as much as 50% of the country's export earnings, making it difficult to implement sound economic and environmental policies (IEA, 2006a,b). Diesel is used as a fuel for power generation in many countries. Davidson and Mwakasonda (2004) summarize the policy issues that need to be addressed to enhance access to electricity for the population in the region. As a part of the study in Zimbabwe and South Africa, they found that the primary limitation is the availability of data on electrification access and usage. The analysis suggests that in order to meet the electrification challenge in the region, a diverse set of technical and institutional approaches would be needed — covering large-scale grid connected extension wherever possible and new developments, together with smaller-scale distributed energy systems using both conventional and renewable energy sources.

One of the major problems of solid bio-fuels is their low status in the energy mix. Every kilogram of dry biomass can replace 0.2 to 0.25 l of liquid fossil fuel (kerosene, petrol or diesel) whether it is for cooking or for power generation. Yet a quarter liter of kerosene is valued highly, for it costs money (cash) to get it. Solid bio-fuel, on the other hand, is obtained by gathering it in plantations and forests, and is virtually cost-free. This has its positive and negative features. The positive feature is that the rural poor can access solid fuels with very little hard cash. The negative feature of "finders, keepers" is that this energy is not valued as appropriately as it should be. If bio-fuels have to play their role as energy suppliers, there is no getting past a situation that they must enter the mainstream of the fuel chain with all the attendant issues of processing and quality. No longer can biomass be accepted with its inherent moisture at 50%. It should be dried and also sized. In short, it must become a standard bio-fuel with its characteristics meant for thermal use displayed — bulk density, calorific value, etc.

The problem of meeting energy needs of the population in SSA is that the communities are widely dispersed and connecting them by grid would be too expensive. Due to transmission and distribution losses the actual delivered cost would be high. It is in this context that decentralized power generation using local biomass fuel would make the greatest sense to fit this requirement eminently.

Use of forest residues and agro-residue utilization is beset with the lack of awareness of successful gasification technology that work in appropriate environments — industrial, institutional or domestic. This is perhaps true of decision-makers, manufacturers and users and hence all the stakeholders. While many other renewables face the issues of "price distortions from existing subsidies and unequal tax burdens between renewables and other energy sources" and "failure of the market to value the public benefits of renewables", and other market barriers such as lack of access to capital, and high transaction costs for making small purchases preventing the creation of a "level playing field", a cliché in renewable energy technologies, bioresidue based technologies have achieved this already — the cost of installation of a biomass based power package varies from 1500 to 2000 USD per kWe Yet the number of successful installations till now has been small and this becomes a key barrier for investments. To top this situation, several earlier attempts that have "failed" have led to potential users shying away from this sector. Hence, the key barriers in the introduction of modern biomass gasification technologies, thermal gasifiers for cottage, semi-industrial applications and electrical gasifiers for quality of life electricity as well as rural industrial activity — are:

- Documentation and evaluating the reasons for earlier failed attempts.
- Very few successful projects using gasification systems for power generation
- Show casing of successful programs of biomass gasification for electrification purpose.
- Lack of adequate scientific and industrial work force to understand, appreciate and provide support in the gasification sector.

*Technical barriers*

There are a number of technical barriers that have to be addressed on a priority basis in order to enhance the credibility of technology packages in the local industry, and to build national capacity to manufacture, build, operate and maintain the gasification system based mini-grids. Some of the key technical barriers are as follows:

- Biomass resource and geographical distribution
  - o Lack of a comprehensive database on the biomass resource available, current usage pattern and possible power potential in all the countries within SSA. This could be in line with the work reported by CGPL (2011). A biomass atlas for the region is an immediate step towards realizing the power potential from biomass.
- Biomass (fuelwood and crop residue) demand (for energy, fodder, etc.) and geographical distribution
- Electricity demand and potential electricity demand (i.e. with electrification) by geographical distribution
  - o There is no comprehensive data on the requirement of the country-wise electricity demand, separately for urban and rural areas.
- Identification of potential areas with good matching between available resource and potential demand for electricity supply
  - o Information is not available on the existing fossil fuel based power generation in the region, which will help in developing strategies for distributed power generation to replace fossil fuel.
- Gasification technical aspects
  - o Norms and standards in terms of renewable energy performance, manufacture, installation and maintenance are weak and/or non-existent.
  - o Local manufacturing capacity and/or assembly of renewable energy technology components are currently lacking, although the knowledge, skills and expertise to operate renewable energy systems are available in the region.
  - o There is a limited technical capacity to design, install, operate, manage and maintain renewable energy based mini-grids.

The only way of overcoming the barriers is to get the key individuals on the technical front as well as the financial front involved in a sequence of activities — awareness, observation of systems working for a reasonable duration, discussions with field operators and investors of successful projects — through a route that makes way for transparent dealings — an academic or research institution. This should be done with a substantial group from each country before it can be said that the ground is ready for the introduction of a technology into a specific country

## Conclusions

Biomass has been in use as a source of energy in the bulk of Africa, mainly for cooking and other thermal uses, with low conversion efficiency. A large fraction of the population in the SSA region is deprived of electricity with no immediate solution to mitigate this problem using conventional energy sources. Efficient use of biomass in Africa can meet both cooking and electricity generation needs. Using a small fraction (~30%) of the existing agricultural and forest residues, distributed power generation potential of about 15,000 to 20,000 MW is possible. Use of efficient distributed power generation technology through gasification could help in meeting the electricity demand. Critical barriers, like resource mapping, capacity building, and technology demonstration, to the introduction of biomass energy in SSA are also brought out.

## Acknowledgments

The author wishes to thank UNIDO for the support and Ms. Gayathri for the help in data collection.

## Appendix 1

| Country/area | Land area | | | | | Inland water | Total area |
|---|---|---|---|---|---|---|---|
| | Forest | | Other wooded land | Other land | | | |
| | | | | Total | With tree cover | | |
| | 1000 ha | % of land area | 1000 ha | 1000 ha | 1000 ha | 1000 ha | 1000 ha |
| Angola | 59,104 | 47.4 | – | 65,566 | – | 0 | 124,670 |
| Botswana | 11,943 | 21.1 | 34,791 | 9,939 | – | 1,500 | 58,173 |
| British Indian Ocean Territory | 3 | 32.5 | 0 | 5 | – | 0 | 8 |
| Comoros | 5 | 2.9 | – | 180 | – | n.s. | 186 |
| Kenya | 3,522 | 6.2 | 34,920 | 18,472 | 10,320 | 1,123 | 58,037 |
| Lesotho | 8 | 0.3 | 31 | 2,996 | – | – | 3,035 |
| Madagascar | 12,838 | 22.1 | 17,054 | 28,262 | – | 550 | 58,704 |
| Malawi | 3,402 | 36.2 | – | 6,006 | 7 | 2,440 | 11,848 |
| Mauritius | 37 | 18.2 | 15 | 151 | – | 1 | 204 |
| Mayotte | 5 | 14.7 | – | 32 | – | 0 | 37 |
| Mozambique | 19,262 | 24.6 | 40,919 | 18,228 | – | 1,750 | 80,159 |
| Namibia | 7,661 | 9.3 | 8,473 | 66,195 | – | 100 | 82,429 |
| Réunion | 84 | 33.6 | 55 | 111 | 18 | 1 | 251 |
| Seychelles | 40 | 88.9 | – | 5 | – | 0 | 45 |
| South Africa | 9,203 | 7.6 | 21,409 | 90,835 | – | 462 | 121,909 |
| Swaziland | 541 | 31.5 | 289 | 890 | – | 16 | 1,736 |
| Uganda | 3,627 | 18.4 | 1,150 | 14,933 | – | 4,394 | 24,104 |
| United Republic of Tanzania | 35,257 | 39.9 | 4,756 | 48,346 | – | 6,150 | 94,509 |
| Zambia | 42,452 | 57.1 | 3,161 | 28,726 | – | 922 | 75,261 |
| Zimbabwe | 17,540 | 45.3 | - | 21,145 | – | 390 | 39,075 |
| **Total Eastern and Southern Africa** | **226,534** | **27.8** | **167,023** | **421,024** | **10,345** | **19,799** | **834,380** |
| Algeria | 2,277 | 1 | 1,595 | 234,302 | – | – | 238,174 |
| Burkina Faso | 6,794 | 29 | 7,427 | 9,178 | – | 4,000 | 27,400 |
| Chad | 11,921 | 9.5 | 9,152 | 104,847 | – | 2,480 | 128,400 |
| Djibouti | 6 | 0.2 | 220 | 2,092 | – | 2 | 2,320 |
| Egypt | 67 | 0.1 | 20 | 99,458 | – | 600 | 100,145 |
| Eritrea | 1,554 | 15.4 | 7,257 | 1,289 | – | 1,660 | 11,760 |
| Ethiopia | 13,000 | 11.9 | 44,650 | 51,981 | – | 799 | 110,430 |
| Libyan Arab Jamahiriya | 217 | 0.1 | 330 | 175,407 | – | 0 | 175,954 |
| Mali | 12,572 | 10.3 | 16,532 | 92,916 | – | 2,000 | 124,019 |
| Mauritania | 267 | 0.3 | 3,110 | 99,145 | – | 30 | 102,552 |
| Morocco | 4,364 | 9.8 | 406 | 39,860 | – | 25 | 44,655 |
| Niger | 1,266 | 1 | 3,740 | 121,664 | 8,000 | 30 | 126,700 |
| Somalia | 7,131 | 11.4 | – | 55,603 | – | 1,032 | 63,766 |
| Sudan | 67,546 | 28.4 | – | 170,054 | – | 12,981 | 250,581 |
| Tunisia | 1,056 | 6.8 | 170 | 14,310 | 2,207 | 825 | 16,361 |
| Western Sahara | 1,011 | 3.8 | – | 25,589 | – | – | 26,600 |
| **Total Northern Africa** | **131,048** | **8.6** | **94,609** | **1,297,696** | **10,207** | **26,464** | **1,549,817** |
| Benin | 2,351 | 21.3 | 3,959 | 4,752 | – | 200 | 11,262 |
| Burundi | 152 | 5.9 | 722 | 1,694 | – | 215 | 2,783 |
| Cameroon | 21,245 | 45.6 | 14,758 | 10,537 | – | 1,004 | 47,544 |
| Cape Verde | 84 | 20.7 | – | 319 | – | 0 | 403 |
| Central African Republic | 22,755 | 36.5 | 10,122 | 29,421 | – | – | 62,298 |
| Congo | 22,471 | 65.8 | 10,547 | 1,132 | – | 50 | 34,200 |
| Côte d'Ivoire | 10,405 | 32.7 | 2,626 | 18,769 | 379 | 446 | 32,246 |
| Democratic Republic of the Congo | 133,610 | 58.9 | 83,277 | 9,819 | – | 7,781 | 234,486 |
| Equatorial Guinea | 1,632 | 58.2 | 31 | 1,142 | – | 0 | 2,805 |
| Gabon | 21,775 | 84.5 | - | 3,992 | – | 1,000 | 26,767 |
| Gambia | 471 | 41.7 | 125 | 534 | – | 0 | 1,130 |
| Ghana | 5,517 | 24.2 | 0 | 17,237 | – | 1,100 | 23,854 |
| Guinea | 6,724 | 27.4 | 5,850 | 11,998 | – | 14 | 24,586 |
| Guinea-Bissau | 2,072 | 73.7 | 236 | 505 | – | 800 | 3,612 |
| Liberia | 3,154 | 32.7 | 0 | 6,478 | 179 | 1,505 | 11,137 |
| Nigeria | 11,089 | 12.2 | 5,495 | 74,493 | 220 | 1,300 | 92,377 |
| Rwanda | 480 | 19.5 | 61 | 1,926 | – | 167 | 2,634 |
| Saint Helena | 2 | 6.5 | 0 | 29 | – | 0 | 31 |
| Sao Tome and Principe | 27 | 28.4 | 29 | 40 | 10 | 0 | 96 |
| Senegal | 8,673 | 45 | 5,001 | 5,579 | – | 419 | 19,672 |
| Sierra Leone | 2,754 | 38.5 | 384 | 4,024 | – | 12 | 7,174 |
| Togo | 386 | 7.1 | 1,246 | 3,807 | – | 240 | 5,679 |
| **Total Western and Central Africa** | **277,829** | **44.1** | **144,468** | **208,227** | **788** | **16,253** | **646,776** |
| **Total Africa** | **635,412** | **21.4** | **406,100** | **1,926,946** | **21,339** | **62,516** | **3,030,974** |

The bold characters and number are to highlight the total sum of certain region.

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