Bioenergy for Sustainable Local Energy Services and Energy Access in Africa

Prospects for commercial biomass gasification in sub-Saharan Africa

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Cover photo: Husk Power Systems gasifier at Kibindu village, Pwani Region, Tanzania (Pol Arranz, July 2019)

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Table of Acronyms

BGMP	Biomass Gasification Monitoring Programme (of UNDP/World Bank)
BSEAA	Bioenergy for Sustainable local energy services and Energy Access in Africa project (FCDO-funded programme)
CFB	Circulating fluidized bed
CHP	Combined heat and power
ESCO	Energy service company
FiT	Feed-in tariff
GEMCOR	Gasifier and Equipment Manufacturing Corporation (Philippines)
HPS	Husk Power Systems (India)
HSE	Health, safety and environmental considerations
IISc	Indian Institute of Science
ITB	Bandung Institute of Technology (Indonesia)
MNRE	Ministry of New and Renewable Energy (India)
NIC	Newly Industrialised Country
O&M	Operation and maintenance
R&D	Research and development
SERI	Solar Energy Research Institute (India)
SSA	sub-Saharan Africa
TERI	Tata Energy Research Institute (India)

Executive summary

Introduction

Gasification is an efficient means of extracting energy from biomass at small scale for producing heat and power. Yet despite the gradual improvement of the process since it was discovered in the 19th century, gasification has had an inconsistent and generally poor commercial track record.

With UK aid support from the UK government via the Transforming Energy Access programme, through Part 2 of the *Bioenergy for Sustainable Local Energy Services and Energy Access in Africa* (BSEAA2) study, researchers led by NIRAS-LTS set out to identify the optimal conditions under which biomass gasification can offer a competitive solution for heat and power generation, to analyse experiences with gasification in various regions of the world and to draw conclusions on the commercial potential for gasification in sub-Saharan Africa (SSA).

Success factors for gasification

Drawing upon research conducted under BSEAA Part 1 and extensive monitoring and evaluation of gasification projects dating back to the 1980s, seven 'success factors' can be identified for gasification to be commercially competitive with fossil fuels or with combustion-based bioenergy systems, particularly for sub-5 MW_e electricity output:

1. **Consistent and affordable feedstock supply.** An uninterrupted supply of feedstock should be available in sufficient quantities of desired quality at consistent price. Uniform size and low moisture content are particularly important for fixed-bed downdraft gasifiers, which are the most widely used design at small scale.
2. **Continuous and sufficient local energy demand.** Gasifiers need to be operated at constant load to maintain high efficiency and acceptable gas quality. This requires a consistent demand for both heat and power, to sustain a reliable anchor load.
3. **Economic competitiveness with alternative energy sources.** There is a fossil fuel price point at which renewable energy becomes commercially viable. But gasification must also be competitive for a given application with other renewable energy options, especially solar PV, considering both the cost of the technology and its long-term operation and maintenance.
4. **Appropriate and reliable technology.** Sophisticated gasifiers with remote monitoring and a high degree of automation are viable in advanced economies where suitable technical capacity exists. Simpler and more robust designs are often considered appropriate for developing countries, because they can be more easily operated and maintained. But gasification is an inherently complex thermo-chemical process and this makes gasifiers more sophisticated than alternative renewable energy technologies - such as direct combustion systems or solar PV installations – making them inherently too complex for many developing country situations.
5. **Realistic business plan.** A realistic business plan is important for determining whether a gasifier project is technically and financially feasible. This requires accurate costings and proper sizing for the applications envisaged. Manufacturers may over-state system up-time and the amount of heat and power that can be produced under actual operating conditions with imperfect feedstock. Project developers can also make unrealistically high projections of energy demand and thus over-state revenue from heat and power sales.
6. **Technology supplier support.** Successful projects require the commitment of the manufacturer for a prolonged period of after-sales support, preferably via a local agent. Prospects for commercial success are maximised if the feedstock supplier, technology supplier, project developer, customer and owner are jointly invested in the venture.
7. **Sufficient operator skills.** Given that gasifier plants are technically complex and can be difficult to operate and maintain, successful projects require motivated owners and plant operators with a commercial motivation to keep the system working. Financial incentives are important to retain trained operators and technicians.

Project status in SSA

The study identifies two main markets for small-scale gasification in SSA: rural electrification via mini-grids and captive power for small industries. In both cases, gasification will usually be a replacement for diesel generators.

Every known project in SSA with a gasifier linked to a reciprocating engine was identified. Most of these 36 projects were based on downdraft, fixed-bed reactor technology. Tanzania and Uganda recorded the highest number of units, with rice husks or maize cobs as the main feedstock. None of these installations are believed to be working on a commercial basis. While some are still technically functional, none are regularly used, and most have been shut down. This reflects a failure to achieve the required success factors. In fact, it would be difficult (if not impossible) to find optimal situations in SSA where all these conditions can be fulfilled, which gives a discouraging prognosis for the future of gasification on the continent.

The high failure rate in SSA can be attributed especially to failure to adhere to strict feedstock specifications (often in order to save money), poor gas quality and yield due to system under-loading and wide load fluctuations, insufficiently skilled operators, a lack of access to support, servicing and spares, and insufficient commitment of project stakeholders, due mainly to a proliferation of grant funding.

Experiences from other regions

The main driver for small scale gasification in Europe was the introduction of subsidies for renewable energy via targeted Feed-in Tariffs (FiT) and Renewable Heat Obligations. This made gasification attractive for small-scale combined heat and power (CHP) applications. Other enabling factors included highly consistent feedstock adhering to stringent quality specifications, a continuous demand for heat and power, a high degree of automation and remote control, and a close and open relationship between manufacturers, researchers and customers. Successful European installations can be found dating back to the 1990s, and a small number of specialised manufacturers are still fabricating small-scale gasifiers for specialist markets, albeit at reduced scale due to the declining value of the available subsidies.

The situation in less industrially advanced countries is similar to that in SSA: despite significant long-term investment in the development of gasification, especially in India, there is a poor track record of commercial sustainability. The introduction of simpler and cheaper technology for developing countries has also introduced significant environmental risks due to contaminants from gas cleaning. The concerted efforts of numerous Indian institutions over four decades have resulted in a more or less standardised gasifier design, which has been disseminated widely in South and Southeast Asia, with minor variations. While relatively simple to operate, this technology has problematic gas cooling and cleaning systems which produce a toxic waste stream and deliver inconsistent power output.

Conclusions for gasification in SSA

The research concludes that small-scale gasification is a bioenergy technology with a disappointing track record in SSA and no plant currently confirmed to be in full commercial operation. Most installations were set up with development finance and have shown mixed and generally poor results.

The global track record of small-scale gasification has been similarly inconsistent over the last few decades. The sector was initially catalysed by rising oil prices and later by global warming concerns and an energy transition toward renewables. Gasification has been most successful where it has been supported by governments, development agencies and research institutions through grants, loans or subsidies, but this has rarely led to commercial sustainability.

Gasification is often considered attractive at small-scale as it is more efficient than direct combustion. But factors such as the need for more complex and expensive technology, the absence of economies of scale in the gasification industry and the lack of technical capacity to operate and maintain equipment, make the technology uncompetitive. This is borne out by observations from numerous plants around the world.

The necessary conditions identified above have never been met in SSA, which explains the widespread commercial failure of the technology. Drawing also upon worldwide gasification experiences from the past 40 years, this gives no room for optimism that gasification can be a commercially sustainable technology for SSA.

Table of Contents

Annexes

1 Introduction

Gasification is one of the most efficient means of extracting energy from biomass at small scale for producing heat or power. Gasification also allows biomass to replace fossil fuels for powering internal combustion engines. In principle, gasification therefore represents a suitable option for any business, project or government seeking to switch to renewable sources of energy for generating electricity or heat. Gasification is particularly well-suited to areas with high biomass productivity, where residues from trees, crops and other plants can be used as feedstock. It is for these reasons that gasification has attracted significant interest in Africa and other developing regions, though with very limited success.

This report sets out to:

a) identify the optimal conditions under which biomass gasification can offer a competitive alternative to heat and power generation using fossil fuels or traditional combustion;

b) analyse gasification projects in countries in sub-Saharan Africa (SSA) covered by the *Bioenergy for Sustainable Local Energy Services and Energy Access in Africa* (BSEAA) study, to determine if these optimal conditions have been achieved, and what this has meant for their success or otherwise;

c) review the experiences of gasification in Europe and selected Newly Industrialised Countries (NICs), to compare with SSA and identify common lessons for replication; and

d) draw conclusions on the long-term potential for gasification development in SSA, on the basis of experiences both in Africa and in other regions.

A basic understanding of biomass gasification is assumed. For further explanation of the underlying principles and the main design features of a gasifier, refer to Annex 1.

2 Success factors for gasification

An extensive analysis of biomass gasification in SSA was undertaken during Phase 1 of the BSEAA study (2016-2017). Having determined that there was no gasification plant in SSA verifiably functioning, that study identified critical barriers to gasification that would need to be addressed in order to achieve commercial viability. This report interrogates, updates and builds upon that analysis. Drawing also upon a landmark four year study of gasification monitoring data from Africa, Asia and Latin America (H Stassen, 1995)[1], seven pre-conditions or 'success factors' can been be identified for gasification to be commercially viable:

1. **Consistent and affordable feedstock supply.** An uninterrupted supply of feedstock should be available in sufficient quantities of desired quality at consistent price. Uniform size and low moisture content are particularly important for downdraft fixed-bed gasifiers, which are the most widely used design at small scale.
2. **Continuous and sufficient local energy demand.** Gasifiers should preferably be operated at constant load to maintain high efficiency and acceptable gas quality. Gasifiers do not operate well with frequent shutdowns and re-starts (see Annex 1). This necessitates a consistent demand for both heat and power, to sustain a reliable anchor load.
3. **Economic competitiveness with alternative energy sources.** There is a fossil fuel price point at which renewable energy becomes commercially viable. Gasification gained renewed interest during the world oil crisis in the 1970s and 80s, when petroleum prices reached historically high levels. Gasification must also be competitive with other renewable energy options, including combustion-based systems and solar PV, considering both the cost of the technology and its long-term operation and maintenance (O&M).
4. **Appropriate and reliable technology.** Sophisticated gasifiers with a high degree of automation and remote monitoring technology are viable in advanced economies where suitable capacity exists. Simpler and more robust gasifier designs are often considered appropriate for developing countries, because they can be more easily operated and maintained. While this may be true in the case of heat production, the same cannot be said for power production, which requires multi-stage gas cooling and cleaning systems to meet the quality requirements of the internal combustion engine. This makes the technology rather complex compared to alternative renewable energy options available in developing countries - such as solar and direct combustion. The relatively high efficiency of gasification compared to these alternatives is often seen as its major benefit, but this is less critical where feedstock is abundant and may be offset by the need for significant hands-on management.
5. **Realistic business plan.** A realistic business plan is important to determine whether a project is technically and financially feasible. This requires accurate costings and proper sizing of the equipment for the applications envisaged. The business model may entail building and operating the plant in close association with local partners, and, in a number of circumstances, transferring the plant to those partners under mutually agreed terms. Some manufacturers over-state system up-time and over-estimate the amount of heat and power that can be produced under actual operating conditions with imperfect feedstock. It is also common for project developers to make unrealistically high projections of energy demand (perhaps wrongly assuming that new industrial activities will become established as a result of the gasification investment), and thus over-state revenue from heat and power sales, in order to secure the commitment of investors or donors.
6. **Technology supplier support.** Biomass gasification plants include the gasifier itself, a gas conditioning system, an engine and various ancillary equipment. Successful projects require the commitment of the manufacturer for a prolonged period of after-sales service to provide technical, material and spare-part support, preferably via a local workshop or agent for rapid response. It is preferable to have a single turnkey supplier who is responsible for installation, training, operation and repair work under warranty. Prospects for commercial success are maximised if the feedstock supplier, technology supplier, project developer, customer and owner are jointly invested in the venture. For example, the feedstock supplier could agree to a long-term contract,

[1] Under the Biomass Gasification Monitoring Programme (BGMP) (1986-1990) run jointly by UNDP and the World Bank's Energy Management Assessment Programme, uniform data was gathered on the performance, economics, safety and public acceptability of biomass gasifiers in Africa, Asia and Latin America.

the technology supplier could guarantee timely after-sales services and spares delivery, the plant owner could provide the site and ancillary infrastructure, and customers could fund the construction of a local grid for power distribution.

7. **Sufficient operator skills.** Gasifier plants are technically complex and can be difficult to operate and maintain. Successful projects require motivated owners and plant operators with a commercial incentive to keep the system working. Financial incentives are important to retain trained operators and technicians, so that the skills required for O&M are not lost after installation.

A pre-feasibility assessment helps indicate whether a project concept is valid and workable. A **screening tool** in the form of a decision matrix was developed by Stassen (1995) (see Annex 2). The matrix guides a step-by-step decision-making process for determining if gasification technology would be the right option based on the specific local circumstances. While the matrix was developed some time ago, the principles remain valid and the matrix can be used with figures that are appropriate for current conditions.

Under the conditions listed above, biomass gasification has the potential to compete with fossil fuels or with combustion-based bioenergy systems, particularly for sub-5 MW_e electricity output. From around 5 kW_e and above, it can also be competitive with solar PV systems. Economic competitiveness is the most critical of the factors listed, and it is through market interventions in the form of renewable energy subsidies that the uptake of gasification was relatively strong in Europe during the 1990s and 2000s (as this report details further).

3 Status of gasification in SSA

3.1 Potential applications

There have been two main applications in SSA for which small-scale gasification has been promoted (IFMR Research, 2010; LTS International, 2017):

1. To provide power to off-grid villages and peri-urban areas; and,
2. To supply captive power for small industries that would otherwise depend on fossil fuel generators, due to lack of grid connection or unreliability of grid supply.

3.1.1 Mini-grids

Rural electrification projects supplying local grids are frequently developed by one organisation and then handed over to another. The project developer may be a non-profit institution such as a government agency or NGO, or a for-profit consulting firm, technology developer or social enterprise. They generally secure funding, install the infrastructure and then transfer the gasification project over to the final operator, which is often a community-based organisation or a cooperative. The owners of the feedstock, operators of the project, suppliers of the equipment and consumers of the services may be functionally separate, which can introduce challenging complications. For example, when a technical or financial problem arises, the local operating organisation may lack the resources and expertise to resolve the situation. As a result, mini-grid ventures have a particularly high failure rate.

3.1.2 Captive power

The captive power opportunity has the potential to be more successful, as it is more likely to be based on private sector financing underpinned by a sound business plan. The industry in question will usually develop the project internally and organise the necessary finance, permitting, contracting, installation and O&M.

These installations can typically provide both electricity and process heat to a stand-alone industrial plant, with excess electricity potentially sold to the grid at a negotiated feed-in-tariff (FiT). Systems serving a company's internal electricity needs eliminate the administrative and operational complications of selling power to multiple customers. These gasification plants will usually be linked to agro-processing or forestry businesses, where the developer owns the feedstock and is also the off-taker of the power and/or heat. The host industry is, therefore, both the investor and the customer.

If power output can be maintained at a high and constant level, by carefully matching supply against demand, gasification can reliably support a base load for the project owner and offer the potential for selling any surplus, provided that there is a sufficiently attractive FiT.

3.2 Project status in SSA

During Part 1 of the BSEAA study (2016-17), 32 projects were identified in SSA with biomass gasification coupled to a reciprocating engine (LTS International et al., 2016). Almost all were based on downdraft, fixed-bed gasification technology, with just three using bubbling, fluid-bed gasifiers. As the necessary operating conditions are similar for both designs, they are addressed collectively in this analysis.

During BSEAA Part 2, the project database was extensively updated and expanded, and operational status was updated for as many of the ventures as possible. A total of 36 gasification projects were identified during this update (see Annex 3). Several of those previously thought to be operational or in the planning stage were in fact abandoned or never actually constructed. Some plants are still technically functional but not commercially operational, so can be fired up if a request is made to do so, but are otherwise not used. It was not possible to locate any plant in SSA that is currently functioning on a regular basis.

Building upon the barriers identified during BSEAA-1 and further investigations during BSEAA-2 via equipment suppliers, project developers and industry informants, the reasons for the failure of gasification in SSA are summarised in Table 1, against each of the success factors described in the preceding section.

Table 1: Situation of gasification development in SSA

Success factor	Situation in SSA
1. Consistent and affordable feedstock supply	• Availability of agro-processing residues such as rice husks and maize cobs fluctuates; they may be unavailable outside the main harvest season(s). • Once a residue becomes used for gasification, prices tend to increase; this can make a plant economically uncompetitive. • In an effort to cut costs, operators seek out the cheapest feedstock, which is likely to affect quality and hence gasifier performance. • Long term contracts for feedstock are rarely in place and availability estimates are generally too optimistic, resulting in supply interruptions and variability in price and quality.
2. Continuous and sufficient local energy demand	• Gasification is most efficient for combined heat and power (CHP) applications, but at African installations there is rarely any heat demand, except for pre-drying feedstock, so there is excess thermal energy (from gas cooling, engine cooling and engine exhaust). • Many gasification projects are located at sawmills because of the availability of wood residues, but the power demand of a sawmill fluctuates widely, which is a poor fit for the steady load that gasification requires. • For mini-grids serving households, electricity demand often peaks during the early morning and evening, but gasifiers are not well suited to intermittent operations; repeated heating and cooling also leads to rapid deterioration of refractory material in the reactor. • Energy demand is often below expectations as customers are not willing to pay for irregular power supply, and because new industrial activities often fail to develop as expected.
3. Economic competitiveness with alternative energy sources	• Due mainly to technical complexity and feedstock costs, the economics of gasification are often not positive compared with fossil fuels to generate power, especially when oil prices are low. • Even if power from a gasifier costs less than from the current system, customers are unwilling to pay if supply is unreliable. • Gasification projects often fail to generate the expected revenues due to low operating hours, rising feedstock prices, unrealistic operating assumptions and high labour costs, especially when compared to a simple diesel generator. • With national governments actively expanding electrification, the national grid often reaches the gasifier location and proves a more attractive replacement for diesel-generated power.
4. Appropriate and reliable technology	• For economic reasons, commercial suppliers of sophisticated gasifier technology from industrialised countries are not active in SSA. Project developers in SSA are also reluctant to consider such technology, lacking the local capacity to operate and maintain it. • As a consequence, most technology in SSA comes from China and India and is more basic. While relatively straightforward to operate, this equipment can be highly polluting (see 4.3 below). • Some manufacturers claim to be able to gasify almost any feedstock, which is misleading and creates false expectations.
5. Realistic business plan	• Projections of system uptime and customer demand in business models are frequently over-optimistic.

Success factor	Situation in SSA
	• Due to the limited success of gasification, some suppliers change their business model. Hybrid solar/biomass systems are introduced, but these bring even more complexity, particularly in managing loads and power phases. • Where a project developer is able to hybridize a system to incorporate solar PV, this may offer a more straightforward solar power solution for local needs, which frequently means that the gasifier is used less than planned, and eventually not used at all.
6. Technology supplier support	• Most technology suppliers design, install and commission the plant, and offer on-site training during construction. They usually provide a one-year guarantee but are not otherwise engaged after installation, and rarely guarantee a minimum number of service hours or minimum power delivery. • In case of technical or operational problems, the operator may lack the means to hire the manufacturer for additional services, such as repairs, spare parts or training of additional personnel. • Only one manufacturer has representation in SSA. This is the Indian company Husk Power Systems (HPS), with a branch in Tanzania, though it is thought to have phased out gasifier manufacture.
7. Sufficient operator skills	• Operators who are properly trained often leave for higher paid jobs, leaving a skills vacuum for the plant owner. • There is often no finance available for additional training from the technology supplier.

Based on the assessment of known gasification projects in SSA, there are none that have been installed under these optimal conditions, i.e. meeting most of the identified success factors. In this respect, factor 2 and 4 are critical. This explains the 100% failure rate that has been observed.

4 Experiences with gasification in selected non-SSA countries

This section analyses the development of gasification for commercial and productive uses in other regions of the world, to assess whether the success factors identified previously are unique to SSA, or if they can be overcome based on experiences from elsewhere. The emphasis is on projects located both in Europe (where successful ventures do exist) and in Latin America and Southeast Asia (where there has been a sizeable uptake but experiences have been less encouraging).

4.1 History of biomass gasification

The discovery of combustible gas led not only to a revolution in lighting and heating, but also to the development of gas-fuelled combustion engines. During the years spanning World War II, between 1930 and 1950, gasification of wood and charcoal was widely applied in response to acute shortages of liquid fuels. The wide uptake of the technology was not indicative of good gasification practice and trouble-free operation, however, and much time was spent on maintaining the gasifiers and overhauling the engines. Gas generators were promptly abandoned as soon as liquid fuels became available again.

The oil crisis of the early 1970s prompted renewed interest in gasification, particularly using agricultural wastes in remote areas of developing countries. The first International Producer Gas Conference was organised in Sri Lanka in 1983, with a second in Indonesia in 1985. Various networks and conferences grew over the subsequent 20 years, but most eventually became dormant due to low success rates and declining interest. A variety of informative technical publications were produced and may still be ordered through the Biomass Energy Foundation Press.[2]

From the 1990s, interest in gasification returned as part of a global shift towards renewable sources of energy in response to climate change concerns. This led to a minor resurgence of interest in advanced gasification technology led by specialised European companies, while the development of simpler technology was spearheaded mainly by Indian manufacturers.

4.2 Experience from selected European countries

The main driver for small scale gasification in Europe was the introduction of subsidies for renewable energy via targeted feed-in tariffs (FiTs) for electricity and Renewable Heat Obligations for thermal energy. This made gasification attractive for small-scale CHP. Several EU countries introduced favourable FiTs targeting bioenergy-generated power, which boosted small-scale gasification in the 50-1,000 kW_e range. Smaller units were directed at individual farmers, wood processing enterprises and cooperatives, while larger systems were designed for district heating, power stations and bigger industries. There was significant interest in Scandinavian countries, where feedstock was readily available from forestry processing industries and the heat could be fully used in district heating systems, while the electricity could be sold into the grid at preferential prices.

Examples of successful European installations and their technology providers are described in Annex 5. The lessons learned from these experiences are summarised in Table 2.

Table 2: Situation of gasification development in selected European countries

Success factor	Situation in Europe
1. Consistent and affordable feedstock supply	• The project operator usually has access to their own feedstock, typically wood residues; it is also possible to buy woodchips at consistent price and quality, complying with defined standards. • Plant operators adhere to manufacturers' fuel specifications, e.g. standardised wood chips or pellets, often dried using the gasifier itself; irregular feedstocks like wood blocks or agricultural residues are not used in Europe.

[2] www.drtlud.com/BEF/bookstore.htm

Success factor	Situation in Europe
	• Nevertheless, long-term contracts for feedstock are rarely in place and availability estimates are generally too optimistic.
2. Continuous and sufficient local energy demand	• In most cases, there are markets for both the heat and electricity, often subsidized, which makes small-scale biomass gasification viable for CHP applications. • Because both heat and power can be used continuously (usually for district heating and the grid) the load pattern is constant, which is advantageous for small-scale gasification. • Per capita electricity and heat demands tend to be higher than in developing countries, further ensuring a significant and consistent load. • There is a long history of gasification and developers and operators have built up experience jointly, making for an open and collaborative relationship, and allowing for the incorporation of minor improvements to fine-tune the technology.
3. Economic competitiveness with alternative energy sources	• Long-term continuous operation provides maximum power and heat production, and therefore favourable economics. • The economics are further enhanced by 'green' funding, including FiTs. • While labour may be expensive, full automation with remote control is common; one person can manage multiple installations. • Commercial projections nevertheless tend to be over-optimistic.
4. Appropriate and reliable technology	• Successful European gasifier plants use standardised technology of modular design, allowing for serial installation. • Most European gasifiers use dry gas cleaning systems that produce no contaminated liquid effluent, unlike those using scrubbers (see below); some produce condensate just before the engine (where the gas is mixed with cool air), but this is relatively clean and produced only in small quantities.
5. Realistic business plan	• As most plants are small (50-150 kW_e) and customers are often individuals or private entities, projects are frequently developed with simple business plans or with none at all. • Installations are generally self-funded, unlike donor-financed projects in developing countries, so there are no perverse incentives to inflate returns or under-state costs. • Typical investment costs are €4,000-5,000 per kW_e, with maintenance costs of €0.03-0.05 per kWh_e.
6. Technology supplier support	• Several technology companies and project operators have close relationships with academic or research institutions to improve their design and operations; projects in Harboøre (Denmark) and Güssing (Austria) (see below) show that this type of collaboration can be a key element of success. • Most technology suppliers design, install and commission the plant, and provide on-site training during all stages and beyond; they often maintain close contact with the plant owner and provide after-sales service when needed.
7. Sufficient operator skills	• Successful projects have strong and motivated management, and operators with sufficient technical skills for O&M. • As most installations are automated, operators need skills in IT and systems control, not necessarily in practical engineering. • The technology supplier is often contracted for regular maintenance, demonstrating their confidence in the equipment.

4.3 Experience from selected low- and medium-income countries

4.3.1 Overview

In low- and middle-income countries, particularly in rural areas, internal combustion engines are widely used for stationary applications, such as generating power and operating water pumps and mills. Technologies like small-scale gasification are therefore of particular interest. These predominantly tropical regions are also characterized by the availability of feedstock as they have conducive conditions for biomass production. In industrialized countries, most stationary applications are powered with electricity from large central power stations. Internal combustion engines are mainly used in vehicles.

These contrasting environments explain the limited interest in using gasifiers for providing power to stationary platforms in industrialized countries. They are more likely to be used to generate power for sale to the grid, as well as heat for on-site use or for district heating. The European context is thus quite different from that in SSA, particular regarding renewable energy subsidies and the way these have incentivised the development of particular applications for gasification.

The operating environment in Newly Industrialised Countries (NICs) might have more in common with SSA, so evaluating experiences in those countries is more relevant when considering the transfer of this technology to Africa. For this reason, experiences with gasification in selected NICs were investigated in BSEAA-1. Those countries were Brazil, India, Indonesia, Thailand and the Philippines. Low rates of success were identified due to five recurring barriers that formed the basis for the ‘success factors’ developed above: feedstock supply challenges, technical issues, unviable business models, inadequate operating skills and insufficient manufacturer support. The BSEAA-1 report proposed opportunities for technological innovation around improved gas cleaning and operational simplification, among others. However, the indications that manufacturers will change their designs are not encouraging. The Indian manufacturer Ankur Scientific, for example, has existed for many decades but its modular gasifier design has not undergone any significant modifications, in spite of persistent gas cleaning challenges.

During BSEAA-2, experiences with gasification were more thoroughly assessed in a wider range of countries. Some have a lengthy history of gasification; some have benefitted from subsidy programs for gasification research or demonstration projects, from which a number of gasifier manufacturers have profited. India stands out as a leader in gasification development and many Indian manufacturers have gone on to introduce their technology in Latin America, Southeast Asia and SSA.

4.3.2 The Indian experience

The development of modern biomass gasifiers in India began in the early 1980s, through the Ministry of Non-conventional Energy Sources (renamed in 2006 as the Ministry of New and Renewable Energy [MNRE]). MNRE supported extensive research and development (R&D) work and subsidised deployment. The first gasifiers were manufactured by Jyoti Ltd and used to power irrigation pumps of 5 to 10 HP. Dr. B.C. Jain, who headed the energy division at Jyoti, left in 1986 to start his own firm, Ankur Scientific Energy Technologies, to focus on the development, manufacture and popularization of biomass gasifiers and solar hot water systems (Ghosh et al., 2004; Shivakumar et al., 2008).

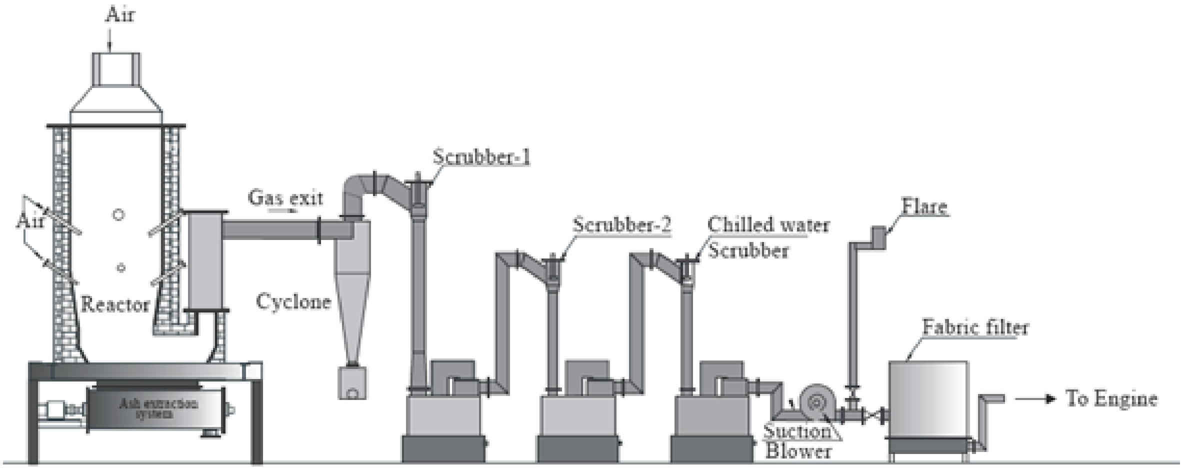
A number of other institutions also started work on gasifiers in the early 1980s. Efforts at the Indian Institute of Science (IISc), Bangalore were initiated in 1981 by Dr. H.S. Mukunda, building on earlier work by the Solar Energy Research Institute (SERI) in the U.S. (SERI, 1979; Shivakumar et al., 2008). This resulted in a novel open core gasifier design that was not feedstock-specific and was eventually disseminated worldwide, including one installation in Ebonyi State, Nigeria (a BSEAA-1 case study). Researchers from the Tata Energy Research Institute (TERI) were trained at Jyoti in 1982 and produced their own 5 HP gasifier in 1984. TERI is known to have supplied at least one gasifier to Tanzania in 2012. Other institutes that worked on gasification included the Punjab and Nimbkar Agricultural Universities and the Indian Institute of Technology in Delhi and Mumbai.

Thanks to consistent government support through MNRE, India had installed around 1,700 units for CHP from at least 20 manufacturers by 2000, using local feedstocks like woody biomass and agricultural residues (Jain, 2000). The two Indian suppliers most active in SSA have been Ankur

Scientific and Husk Power Systems. Information on these companies and experiences with their technology outside SSA has been compiled in Annex 6.

The concerted efforts of numerous Indian institutions over four decades have resulted in a more or less standardised Indian gasifier design (Figure 1). It typically consists of a reactor, one or two cyclones, gas scrubbers (mostly water-based), a suction blower with a flare for initial start-up, and a gas filtering system.

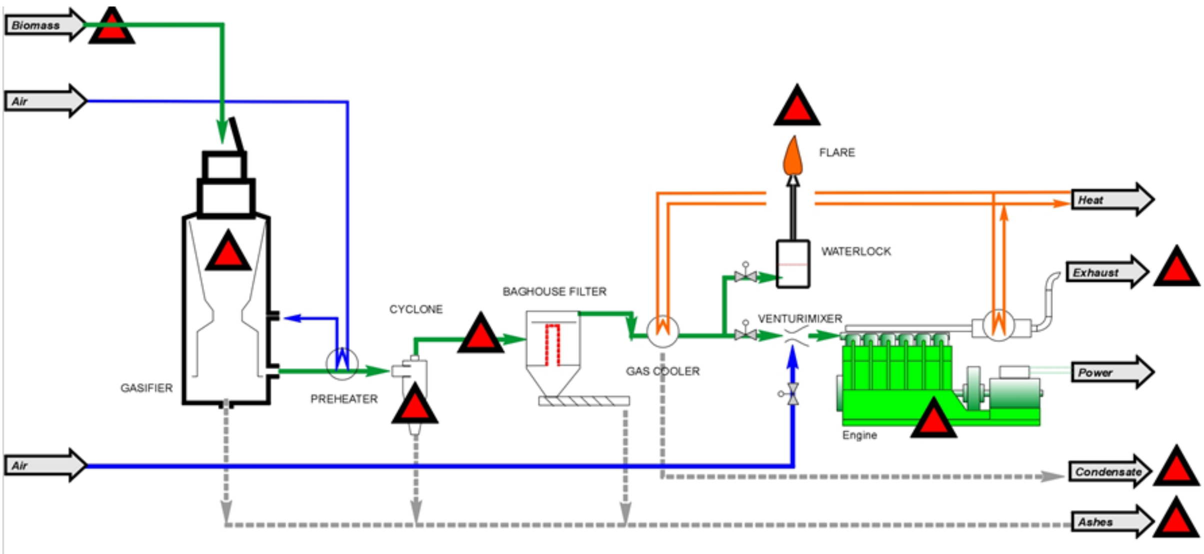
Figure 1. Typical configuration of an Indian biomass gasifier



Source: Dasappa, S., Subbukrishna, D. N., Suresh, K. C., Paul, P. J., & Prabhu, G. S. (2011)

Systems such as these have been disseminated widely in South and Southeast Asia. Several have also been set up in SSA. The essential difference between these systems and those manufactured in Europe and the USA (see Figure 2) is the method of gas cooling and cleaning. In the Indian design, most of the particles are removed at high temperature in the cyclone(s) and the gas is then processed through scrubbers and filters. More advanced systems use a dry gas cleaning system.

Figure 2. Typical configuration of a biomass gasifier with dry gas cleaning



Source: (Knoef & Vos, 2009)

In the typical Indian design, the gas is first passed through one or more water scrubbers for cooling and cleaning of tar and particulates. This is a simple process but produces highly contaminated wastewater. Most manufacturers claim that the cooling water is recirculated with zero discharge, using simple treatment and occasional pH adjustment. But complete breakdown of the tar within the gasifier is unlikely, so tar inevitably accumulates in the scrubber water and must be treated to keep the quality acceptable for recirculation. It is first pumped to a flocculation tank and treated with activated carbon, alum and polyelectrolyte, then passed through a sand bed filter. The clear and odourless water, free of tar and particulates, is then taken back to the sump for recirculation. There are often problems with this system due to blockages of valves and pumps, and accumulation of toxic solids in the flocculation tank and filter. Ankur Scientific introduced an alternative dry gas cleaning system at a recent installation in Cuba, but performance data is not yet available.

After cooling and scrubbing, the gas is passed through a fixed bed filter to remove final traces of tar and particulates using sawdust, charcoal, rice husk, oil, fibrous organic or metallic materials. These filters are again simple and efficient, but create a number of problems over time:

- The filter becomes blocked by the captured particles and needs to be replaced. While equipment suppliers advise replacing the filter medium after a certain number of operating hours, the increasing particle load causes a gradual drop in pressure and engine power, which gets worse over time. Several plants have had to be abandoned as no suitable material was available to refresh the filters.
- When the system is operated under a partial load, the gas temperature tends to decrease to the point where condensation may take place at the filters, causing further pressure loss and potentially resulting in stoppage of the engine.
- There is usually no proper solution for disposing of the contaminated filter material. Some operators burn it or even use it to fuel to the gasifier.

These bottlenecks with gas cooling and cleaning mean that this technology will always produce an inconsistent power output, and a liquid and solid waste stream containing toxic constituents as an undesirable by-product. South Asian manufacturers generally offer a one-year warranty against technical failures, but it is telling that they never guarantee a minimum performance level, such as an assured number of kWh of output per year.

The lessons learned from gasification experiences in India are summarised in Table 3 against the seven identified success factors.

Table 3: Situation of gasification development in India

Success factor	Situation in India
1. Consistent and affordable feedstock supply	• Lack of organised feedstock suppliers, especially for wood residues. • Insufficient quantities of feedstock meeting necessary parameters. • Absence of long-term contracts for feedstock supply, with availability estimates generally too optimistic. • Lack of adherence to fuel specifications by plant personnel.
2. Continuous and sufficient local energy demand	• Rarely any heat demand, except sometimes for parboiling rice or for miscellaneous industrial activities needing hot water or low-grade steam. • Other constraints in SSA are also valid for India (see Table 1).
3. Economic competitiveness with alternative energy sources	• Projects often fail to generate expected revenues due to low operating hours, rising feedstock prices, unrealistic operating assumptions and high labour costs. • Labour costs reflect the higher O&M needs of gasifiers compared to diesel gensets. • The national grid is continually expanding and often reaches the gasifier location and proves a more attractive replacement for diesel-generated power.
4. Appropriate and reliable technology	• There are over 20 gasifier suppliers in India; some (e.g. IISc) have licensed satellite manufacturers. • Some manufacturers claim to be able to gasify almost any type of feedstock, which is misleading and creates false expectations. • In many cases, gasifiers are coupled to existing diesel gensets to operate on a dual-fuel basis; the O&M of the gasifier is often

Success factor	Situation in India
	seen as an additional burden by the operators, who receive no incentives to make the gasifier work effectively. • As a new technology is involved and there is limited collective experience in its operation, there is a tendency for customers to hold the supplier responsible for almost everything. • Gasifier operation is relatively complex and requires adherence to specific feedstock parameters and O&M procedures, for which sufficient oversight is often not availed. • Some operational features are dirty, laborious or dangerous for the workers, especially in small scale batch-wise units, e.g. poking the fuel bed, removing ash and char, and handling condensate.
5. Realistic business plan	• In trying to protect their intellectual property, technology developers often fail to impart sufficient information and skills to operators for them to manage their installations properly. • Suppliers and technology developers are often reluctant to divulge past failures to potential customers, creating unrealistic performance expectations in order to win sales. • Equipment manufacturers often consider gasification a side business that complements their core business (often supplying combustion-based equipment or dryers), and are not willing to put in substantial effort and financial resources; but customer confidence requires them to be an active partner. • If the project developer or owner is able to source funding to hybridize their gasifier system by introducing solar power, the gasifier becomes used less than originally planned, and eventually not used at all. • Projections of uptime and customer demand in business models are frequently over-optimistic.
6. Technology supplier support	• Most technology suppliers design, install and commission the plant, and provide on-site training during construction; they usually provide a one-year guarantee against defects, but this does not extend to assured power output or a minimum number of operating hours. • As technology providers are rarely financially involved, they tend to be more focused on making sales than in remaining active, long-term partners. • Some have regular contact with the plant owner and can provide after-sales service or training of additional personnel, as long as the plant operator can pay. • Others provide inadequate training of operators and fail to offer prompt and reliable after-sales services.
7. Sufficient operator skills	• In village installations, there is a lack of interest and capacity within the community to manage the day-to-day running of a power plant. • Managers often assume that operating the plant is straightforward and under-estimate the role of training. • There is often frequent changeover of operating personnel. • When systems are performing well, there is a tendency to take liberties with O&M procedures; significant damage can occur to vital components if feedstock specifications and O&M instructions are not strictly followed.

4.3.3 Other low- and middle-income countries

Annex 6 contains several case studies from other low- and middle-income countries, describing their experience with small-scale biomass gasification. A summary of the lessons learned from these case studies is provided in Table 4.

Table 4. Key lessons from case studies in selected low- and middle-income countries

Location/Supplier	Gasifier type	Scale (kW_e)	Learning points
SME Renewables, Cambodia	Downdraft, local version of imported technology	10-50	• Local manufacture reduces costs and accelerates development of a local gasifier market. • Such development should preferably take place in conjunction with a local knowledge centre, to build local technical skills and manufacturing capacity.
Sembubuk, Indonesia	Downdraft, imported	<50	• Technical problems resulting in prolonged equipment shutdown have a demotivating effect on owners and operators. • Gasifiers should only be installed at sites with commercial heat or power demand.
Bandung Institute of Technology, Indonesia	Downdraft, local manufacturing	10-25	• Extensive support from a local technical institution can be very helpful. If villagers partly invest in the installation, it can create motivated operators.
Brazil, Philippines	Charcoal gasification	5-10	• Gasifying charcoal is simpler and cleaner than wood or agricultural waste; it is an interesting small-scale option if charcoal is reasonably priced.
GEMCOR, Philippines	Downdraft, wood-based	5-10	• Gasifiers are not well suited to fluctuating loads, e.g. irrigation systems and certain rural industries.
CENBIO, Brazil	Downdraft	5-10	• There is insufficient local technical capacity to properly operate imported gasifier technology.
Thailand	Downdraft, rice husk & wood, mostly imported	10-100	• High tar content is the major technical problem. Other barriers are non-technical, e.g. insufficient feedstock, high feedstock costs (e.g. rice husk), lack of trained operators for imported plants.
China	Downdraft, rice husk & wood	25-150	• Rice husk gasifiers can be successful in a local market if there is relatively easy access to back-up services, and if there are no local standards in place for disposal of scrubbing water.
Indonesia	Downdraft, mostly wood	10-150	• Interest in gasification rapidly declines with expansion of the electricity grid.
Vanuatu, Pacific	Downdraft, mostly wood, imported	10-25	• Technology can be successfully imported if there is a long-term technical expert and externally funded institutional support (in this case the EU).
Dogofiry, Mali	Downdraft, rice husk, imported	150	• As above, the technology can be successfully imported if there is a long-term technical expert (in this case a Chinese operator).
Seychelles	Downdraft, coconut husk & shells, imported	25	• Imported gasifiers must be proven to work with local feedstocks; in this case, an imported wood gasifier was supposed to operate on coconut husk and shells, but this was not pre-tested and resulted in technical problems.
Burundi	Downdraft, peat	35	• Again, imported gasifiers must first be proven to work with local feedstocks. In this case, it was meant to use peat as feedstock, but high ash caused technical problems.

5 Comparison of gasification in SSA with other regions

5.1 Methodology

At the sub-5 MW scale, gasification is a highly efficient way to produce electricity. Yet while small- to medium-scale gasification has been widely adopted in South and Southeast Asia, and in some industrialised countries, there are no gasifiers in SSA that have been operating reliably over a period of years. This chapter provides a qualitative analysis of why this is the case, with reference to the identified success factors. The assessment is based on the cited literature, critical reviews and the author's personal experience.

5.2 Feedstock quality and availability

A technically viable gasification system hinges on the supply of feedstock of reliable quantity and quality throughout the year. The most suitable feedstocks for gasification are dry wood particles, charcoal and, with appropriate equipment, rice husk (H Stassen, 1995). The primary feedstock in Europe is therefore highly standardized wood chips or biomass pellets of specified size distribution and moisture content. The success story in India is similarly based on the use of standard fuel, in that case rice husk. Specific fuel consumption of gasifier systems with internal combustion engines ranges from 1.1 to 1.5 kg per kWh when fuelled with wood, and from 1.8 to 3.6 kg/kWh when using rice husk.

In SSA, there has been much more feedstock variety, with different projects using maize cobs, coconut shells, sawdust, bark, wood waste, peat, straw, corn stover, peanut shells, cashew shells and other agro-processing residues. This reflects fluctuations in seasonal availability and competing uses. Many of these feedstocks have not been fully evaluated by equipment manufacturers. Donors may have seen gasifiers operating successfully in India for rural electrification and small industries, and have then supported companies like Ankur Scientific and Husk Power to extend their technology to SSA. But the feedstocks in SSA are often quite different and insufficiently tested.

Companies may claim that various feedstocks can be used in their gasifiers, but this conclusion is often based on limited testing and the equipment frequently proves highly sensitive to fuel size, moisture content, density and morphology. Operators also tend to relax strict fuel specifications over time, perhaps because they are unaware of the importance of standardisation, or because the correct preparation methods are too labour-intensive (such as chopping logs into small, uniform sticks).

The demand for biomass resources for other purposes needs to be considered when setting up a gasification project, as competition can cause price rises and feedstock scarcity. There are also examples were official bodies give wrong information on feedstock amounts, contributing to over-optimistic feasibility studies (T. Helle, Novis GmbH, personal communication). Some agricultural residues also play an important role in sustaining soil structure and fertility, meaning that their removal for gasification can negatively impact nutrient availability and agricultural yields.

In India and several Southeast Asian countries, gasifiers have been operated successfully at rice mills. These represent viable sites as:

a) the owner of the mill is also the owner of the feedstock;
b) the feedstock is standardised; and
c) the mill consumes the electricity produced, and sometimes also the heat for par-boiling rice.

(Ghosh et al., 2004).

With the feedstock supplier also the operator of the project, feedstock supply is assured. If the feedstock is not owned by the operator, however, it is essential to establish long-term supply contracts to avoid fluctuations in quantity, quality or price.

In summary, a consistent and affordable supply of feedstock is essential for a successful gasification project. This is well understood in India and Europe, yet frequently overlooked in African installations, with significant adverse effects on gasifier performance.

5.3 Continuous and sufficient local energy demand

To prolong the lifetime of a gasifier and to ensure the highest possible gas quality, it is important that the plant is operated at a continuous load close to its maximum rated capacity. A gasification system operated at 50% loading cannot achieve the required reactor temperature, which results in high tar levels and inferior gas composition.

It is for this reason that most gasifiers in industrialised countries are set up to provide both heat and power on a continuous basis, with operating times upwards of 7,000 hours per year and interruptions only for scheduled maintenance. A connection to the national grid allows excess power to be sold when required, and the heat can often be fully utilised for district heating and/or for drying feedstock.

These basic technical limitations are not always understood, as evidenced by the installation at the Nyabyeya Forestry College in Uganda, where a 50 KW_e gasifier was installed at a site with peak electricity demand of only 20 kW_e (Kasedde, 2009). Perhaps the college owners believed they could benefit from the excess power, but were not aware of the problems caused by operating a gasifier at 30-40% of its rated capacity. Some applications (e.g. sawmills) are inherently poorly suited to biomass gasifiers as their power demands are highly variable (see Annex 5). This is the case in most installations in SSA, meaning that the gasifier is shut down and started up several times per day, with detrimental effects on the lifetime of the metal, concrete and ceramic components of the reactor. This also affects the quality of the gas, as relatively large quantities of tars are produced during each start-up cycle. Some Chinese suppliers provide a gas storage buffer of 5-10 m^3 so that the equipment can be run continuously, but this introduces a risk of fire or explosion. Lacking the option to feed power to the grid, most gasifiers in SSA cannot be usefully operated for more than 3,000-4,000 hrs/yr.

While plant owners may see their gasifier as a full replacement for a diesel genset, a fluctuating load or frequent shutdowns and re-starts mean that tar production is unacceptably high. The only viable feedstock under these circumstances is charcoal, because it does not produce tar (Milne et al., 1998). But charcoal is a commercially traded fuel in high demand for domestic cooking, and is seldom available at viable prices.

In summary, a gasifier requires continuous high loading for clean and efficient operation, so it is important that there are available off-takers for the full output of power and heat, especially if the on-site load fluctuates or is discontinuous.

5.4 Economic competitiveness with alternative energy sources

The main driver for the development of gasification in the 20th century (evidenced by multiple patent applications in the 1970s and 80s) was rising fossil fuel prices. Developments in the 21st century have been driven more by the push for renewable energy, in light of climate change concerns.

In Europe, renewable energy is supported with fiscal incentives such as FiTs and subsidies for district heating. Biomass gasification is then no longer in competition with technologies driven with fossil fuels, but with other systems that use renewable sources such as wind, solar, geothermal and hydro power. Subsidies for renewable energy have been declining as the industry matures, making the bioenergy market more competitive, not only for gasification but also for other bioenergy technologies.

In tropical regions, including SSA, the development of gasification was often supply-driven, motivated by project developers and international donors seeking to make use of biomass residues that were at one time abundant and available free of charge. Those biomass supplies have been squeezed by growing local demand for other uses, and other renewable energy technologies have since been introduced that are less complex to use, especially solar PV. This has reduced the competitive space for gasification as a power solution.

At least one technology supplier (Husk Power Systems) has introduced hybridized solar/biomass systems in response. But there are strong indications that the usage of the solar power is preferred as it is more familiar and reliable than the accompanying gasifier. Solar PV systems have become increasingly common throughout rural SSA, supported by suppliers and installation companies with well-trained technical personnel with access to ample supplies of spare parts. These hybrid installations have thus eventually become solar power plants. A technologically simple option like solar is preferred over a potentially cheaper but more complex option like gasification.

There are also technical constraints with dual-system installations, as solar PV tends to be used for loads up to 5 kW_e, which is the minimum capacity where gasifiers become feasible, meaning that hybrid systems face inherent technical challenges of load management and the above-mentioned problems caused by under-loading of the gasifier.

In Tanzania, Husk Power has sought to operate as an energy service company (ESCO) that owns the gasifier for a certain period of time and provides energy services jointly with the project developer (Jain, 2000). Projects set up in this way can stimulate adoption of the technology, but require the ESCO to have significant capital to pre-finance a pipeline of multiple installations.

With more installations, economies of scale will lower the investment cost and more collective experience can be gained with the technology. This will have a positive feedback for further replication. But the fact that many gasification installations in SSA are fully or partly paid for using donor funds, with consumers paying little or nothing for the power, makes it difficult to ascertain true viability and may impede replication in a non-subsidised environment. Replication is further constrained by the uncertain availability of affordable feedstock, insufficient commercial energy demand, lack of skilled personnel, unreliable technology and the absence of manufacturer support with reliable supply of spare parts.

One of the main drivers for biomass gasification in SSA and other low- and middle-income countries is the absence or unreliability of grid power. However, the past decade has seen a dramatic acceleration in national grid connectivity in many SSA countries, such as Tanzania, Uganda, Zambia and Kenya. Around ten of the identified gasification projects in SSA were decommissioned after the arrival of grid electricity. Even if the grid is present but unreliable, it usually still offers cheaper power than a small-scale gasifier. So users may still prefer to use grid power and adjust their consumption to match the periods of grid uptime.

The economic advantage of a small-scale power gasifier depends on the potential savings from switching from high-cost commercial fuel to low-cost biomass that is locally available. These savings have to compensate for the higher costs of the initial investment, labour and O&M. Biomass gasification projects are therefore difficult to realize on a financially sustainable basis. The key factors determining the comparative economics are: the price of feedstock, the price of diesel, the price of alternative power sources (PV or grid electricity) and the load factor. Fuel costs, operating hours and load factor are interrelated. For example, a high number of annual operating hours or a high value of the load factor can compensate for cheap alternative power (from PV or grid) or high feedstock costs.

5.5 Appropriate and reliable technology

In Europe, there are niche applications where biomass gasification is appropriate because of the higher energy efficiency that the technology can achieve at small scale compared to other bioenergy options such as combustion. Availability figures of at least 7,000 hrs/yr are possible with a high level of automation and process control, allowing for remote operation and continuous energy production. The investment in automation is offset by avoided labour costs.

Achieving such high operating time requires abundant and continuous feedstock supply, as already discussed. Gasifiers can therefore often be found at mills (in particular sawmills and rice mills) because they have reliable access to uniform feedstock, in-house technical staff and a demand for the energy produced. Seasonality of crop processing may nevertheless reduce operating capacity.

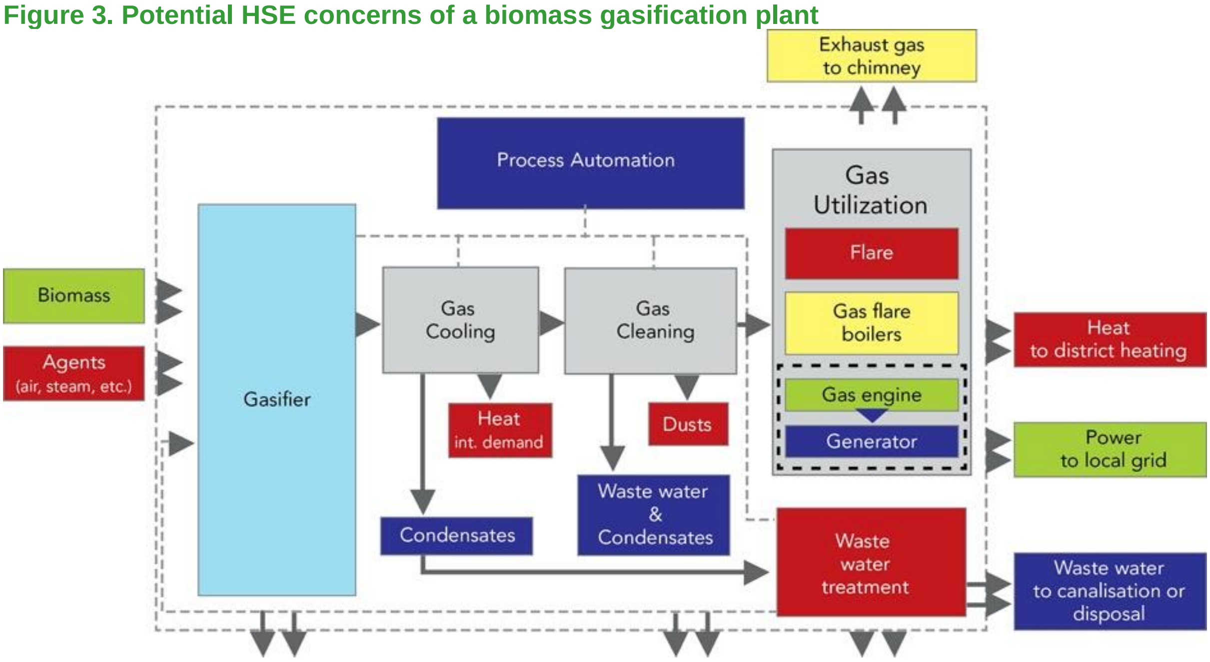
Biomass gasification is often promoted as robust, efficient and straightforward, but the gas cleaning pitfalls of over-simplification have been highlighted in section 4.3.2 with reference to the standard Indian design. Solar PV systems are now available in SSA for less than US$0.50 per installed Watt of power. These systems are largely maintenance-free, except for the cleaning of panels. In contrast, a gasifier relies on a complex energy chain that needs to be functioning well, starting with feedstock collection, preparation and feeding, through to thermal conversion, gas cleaning, gas cooling and mixing with secondary air and, finally, the reliable operation of the engine and generator (see also Annex 1). This complexity, compared with the alternatives, has brought great challenges for operators. The process of gasification is inherently too complex for simple equipment that can be managed with limited technical capacity.

To be supported and sustained more reliably, the gasification technology should be locally available within the country of installation, even if originally imported, and there should be a local agent able to provide training, spare parts and servicing support. They could organize service teams to monitor several plants within a given radius of regional workshop facilities. Local manufacturing under licence can also be successful, as SME Renewables in Cambodia has shown (see Annex 6), but this can result in poor quality installations, and will only be viable if low-cost materials for fabrication can be found on the local market (Dimpl et al., 2011; Salam et al., 2010).

There are many health and safety issues to take care off with gasification, and disposal concerns for liquid and solid residues (Kasedde, 2009). Research at Cambodian enterprises that had installed gasifiers to generate shaft power or electricity from wood or rice husks showed that people were "largely unaware" of the negative impact of gasifiers on health and the environment, and hence did not take any action to treat tar and wastewater (Dimpl et al., 2011). Like the case study in Mali (Annex 6), the land around many gasifiers in Cambodia was heavily polluted with black tar and wastewater, which in several cases was draining into local watercourses. Toxic leaks of carbon monoxide (CO) were frequently observed, risking the safety of operators (ibid.). A commercial biogas provider in Germany installed an Ankur gasifier from India and fed it with woody biomass that was not appropriate for their biogas equipment. But the Ankur plant (which was installed in a closed hall due to the cold climate) emitted so much CO and other toxic gases that the company had to stop its operation (Hasenstab, 2008).

In Europe, a Guideline on Health, Safety and Environmental (HSE) aspects of gasification has been developed. Figure 3 illustrates the various HSE aspects of a simplified gasifier installation.

Figure 3. Potential HSE concerns of a biomass gasification plant



Source: (Knoef & Vos, 2009)

There is a tendency to transfer combustion standards to gasifier installations, with the risk that pollution threats unique to gasification are not adequately covered. Denmark is the only European country with specific environmental emission standards for gasification. In most developing countries there are no standards at all, although there is increasing awareness of the environmental risks of operating poor quality gasification systems.

Small-scale biomass gasifiers need to be simple, reliable and easy to maintain. The inherent complexity of a gasification installation can largely be overcome by automation and process control, taking HSE issues into consideration. Biomass gasification is particularly interesting at small scale due to its high conversion efficiency, but size reduction is unfortunately not accompanied by a reduction in operational complexity.

5.6 Realistic business plan

A detailed business plan may not be necessary if the investor is familiar with the technology, has access to their own feedstock and intends to use most of the energy internally. This is often the case at small industries like sawmills and rice mills, where funding may be privately sourced via informal lending channels.

Business plans will, however, be necessary to attract formal loans or investment finance, and will require technical and financial feasibility studies (with sensitivity analyses), a biomass supply management system, a waste management plan and sometimes an Environmental Impact Assessment. Banks will also require collateral. Given that the assets of a gasification plant will usually be insufficient to cover the investor or lender's assessed risk, the requested collateral value may be significant.

Business plans are often overly optimistic, in order to attract investment or loan finance. Experience from plant owners highlights the following factors as most likely to undermine projected performance and revenues:[3]

- plant completion dates are delayed when problems occur with delivery, customs clearance, permitting or commissioning;
- feedstock security and quality is seldom guaranteed as (e.g.) the supply of feedstock is not sustained throughout the year, price increases due to a competing use, or the operator does not respect the fuel specifications of the technology supplier;
- long-term feedstock supply contracts are desirable for investor confidence, but may tie the operator into a high fixed price; developers may therefore choose to combine spot market purchasing with an assured supply, to deliver base figure security;
- energy demand is often much lower than envisaged because the local grid is not fully constructed, the number of households willing or able to be connected is lower than expected, or per-household consumption is lower than foreseen;
- users are unwilling to pay for unreliable and interrupted power, so revenue declines;
- there is no way to recover debt from non-paying customers, so they are cut off and a negative feedback cycle is perpetuated;
- declining oil prices reduce the costs of fossil fuel alternatives;
- the technology underperforms and O&M requirements are higher than foreseen, with knock-on impacts on operating hours;
- operators' skills are not sufficient; and
- the stakeholders in the project lack the required knowledge, expertise and motivation to make the venture work when difficulties are encountered.

Such negative experiences have contributed to the conversion of some gasifiers in SSA to hybrid systems, as previously described.

The involvement of all stakeholders, from the early design phase through to commissioning and operation, is one of the cornerstones of success. Ownership status and operational responsibilities must be clear from the start, with a shared understanding through contracts and agreements between the intended technology supplier, operator, biomass providers and energy consumers. While this seems obvious, such provisions do not always exist in projects in SSA, especially where low-cost or no-cost development finance has been provided.

Even if donor funds are available, some form of financial commitment from the stakeholders is still beneficial. If the primary feedstock supplier has a meaningful stake in the project, for example, they have a vested interest in supplying the fuel at a reasonable price that will ensure the venture remains viable. Likewise, if villagers invest in a mini-grid, they will be motivated to keep the plant operational and take over part of the O&M.

In developing countries, project developers (often NGOs) are mostly involved in the initial stages but then withdraw and hand over to the operator. The Build, Own, Operate and Transfer (BOOT) model has been recommended in India for public-private partnership projects, adapted from large-scale infrastructure projects (Jain, 2000).

Project developers and implementing agencies must be aware of the risks and responsibilities concerning potential environmental damage from gasification plants, and strict environmental protocols must be guaranteed. In this respect, it is surprising that UNIDO specifically requested a wet scrubbing system rather than a dry gas cleaning system in the technical specifications for a 150 kW_e gasifier installation in Cambodia (UNIDO, 2011).

[3] Several of these issues are valid not only for gasification investments, but also for other renewable energies.

In summary, the business model requires accurate cost figures and proper equipment sizing. The chosen technology needs to be mature and user friendly for SSA, as local technical capacity is usually limited. Installation must be accompanied by dedicated capacity-building support. Development partners have a tendency to cover only the hardware and not the necessary training, education and awareness-raising. One project developer estimated these additional needs would increase costs by 30-40% (T. Helle, Novis GmbH, personal communication).

5.7 Technology supplier support

Suppliers of gasification technology in industrialised countries are keen to maintain their reputation by providing high-quality equipment. Some have service teams who provide after-sales support and regular maintenance visits to their clients, in the same way as a home appliance provider would offer a service package at the time of sale. Many installations are installed on a turnkey basis and the supplier can then be held responsible for malfunctions as well as training and after-sales support.

The situation is different in SSA countries, where most gasifiers are imported, usually from India and sometimes from China and the USA. The plants are constructed over a period of 1 to 2 months, with local personnel trained concurrently in O&M. After commissioning, the installation is typically transferred to the customer with a small stock of spares and a one-year guarantee. The guarantee is often unclear on what exactly is covered, especially when the supplier is in a distant country and lacks the means to provide in-person follow-up.

Most problems begin after the end of the first year, when operational difficulties arise but the spares have been used up. Foreign technology suppliers usually have no local service office to provide after-sales service, so all materials must be ordered from overseas. This is often problematic, not only in terms of communication, but also from the practical point of view due to funds transfer, equipment shipment, customs clearance and domestic transport. It can take months before the required parts arrive. If the issue was serious then the plant will have been mothballed in the meantime, leaving no income for the operators – who might have left for more attractive opportunities.

Foreign technology suppliers can only justify a local branch if they have a minimum critical mass of installations, or if they are sufficiently well funded to be able to take the risk of establishing local representation to develop the market more intensively. Only Husk Power Systems has so far taken this step (with its office in Tanzania), but is now believed to have dropped gasifier promotion in favour of solar PV development.

Technology suppliers have shown reluctance to accept suggestions for technical improvements. They have a tendency to claim that their technology is mature and that any problems must be related to local issues like unskilled operators, failure to respect manufacturer's operating specifications or incorrect maintenance protocols.

There is currently no commercial manufacture of gasifiers in SSA, although the necessary expertise to fabricate renewable energy systems is available in some countries, such as South Africa. The lack of technical and institutional support within the continent hampers implementation and management of biomass-based gasifier systems, and is one of the main reasons for systems not working.

5.8 Sufficient operator skills

Small-scale biomass gasification consists of different stages, from fuel feeding through to reactor operation, gas cleaning, gas cooling and engine management. Operating such plants requires significant labour compared with a diesel genset or other renewable energy options. The regular cleaning of filters bags or replacing solid filter materials is a particularly dirty and cumbersome job. The service intervals for gasifier installations are shorter than for alternatives, which requires high operator discipline. Operational problems like fuel irregularities or load fluctuations may occur unexpectedly, so the site team must be sufficiently skilled to troubleshoot and respond quickly. Operators therefore need thorough training in the principles of gasification and the O&M requirements of the plant in question.

Due to the complexity of the process, most gasifiers in industrialized countries are fully automated and can be operated remotely, with a service team handling regular planned maintenance. Given the lower price of labour in developing countries, automation is less important to the economics of running a gasification plant. Project developers in SSA do not usually favour automated technologies as there is limited knowledge of how to keep such systems working, and internet connectivity may be unreliable. In case of malfunction, the foreign technology supplier needs to be consulted and this can be time-consuming and expensive. Automated systems may also contain components that are unknown locally. Sophisticated Otto gas engines were installed at an Italian-funded project in Indonesia, for example, with a high rate of failure as there was no technical and infrastructural support to maintain them (see Annex 6).

Most plants are abandoned for want of technical personnel for O&M, once they become familiar with the cumbersome work required. Unless the plant operator can retain these staff by offering higher wages, they will be left with a skills gaps. Manufacturers must provide an O&M manual in the local language and keep it updated if any modifications are introduced. The operator must adhere to the manufacturer's specifications and follow the instructions provided. Dedicated personnel and motivated operators are essential to keep the gasifier installation in good condition.

A typical problem is failure to respect strict feedstock specifications, perhaps due to cumbersome pre-treatment requirements. The cleaning of filters is another source of operational problems as it is dirty work with health and safety implications.

In summary, operating a biomass gasifier plant is not as simple as running a diesel genset. Owners must be aware of this and motivate operators and technicians to secure proper operation by providing appropriate incentives, such as salary top-ups, free access to electricity or a stake in the project.

5.9 Transfer of critical success factors to SSA

There are a handful of examples of successful gasification plants in industrialized countries, but few can be found elsewhere. Table 5 analyses what would need to happen for the critical success factors from these successful installations to be transferred to SSA.

Table 5. Transfer of critical success factors in SSA

Success factor	Critical issues	Recommended action for transfer to SSA
1. Feedstock quality and availability	Quantity	Arrange long-term contracts with suppliers or ensure that the feedstock supplier has a stake in the project
	Seasonality	Arrange to stockpile feedstock
	Quality	Prepare feedstock as specified by the manufacturer
	Sustainability	Avoid field residues that would otherwise be recycled
	Logistics	Arrange harvesting, collection, transport and pre-treatment
	Costs	Secure long-term supply contracts; use realistic costings
	Awareness	Respect feedstock specifications
2. Continuous and sufficient local energy demand	Continuous load	Avoid load fluctuations
	Minimum load	Operate at >60% rated capacity using parasitic load
	Maximise demand	Evaluate options for heat recovery and use
	Awareness	Ensure operator understanding that low system loading leads to poor gas quality and shortened equipment lifetime; do not use gas buffer storage
3. Economic competitiveness with alternative energy sources	Viability	Conduct detailed financial feasibility assessment, including sensitivity analyses on feedstock costs, energy demand, diesel price, grid and PV power costs, operating hours, lifetime, etc.
	Stakeholder involvement	Ensure that stakeholders have a meaningful investment in the project
	World oil prices	Not controllable
	Financial incentives	Confirm which subsidies apply and whether they are sufficient to give a competitive advantage over fossil fuels or other renewables
	Grid power	Evaluate grid electricity costs and grid expansion plans. Investigate frequency of blackouts
	Cheap alternatives	Evaluate cost of alternatives (e.g. solar PV). Inform government policy towards grid expansion and hybrid systems
	Replication potential	Ensure meaningful share of investment paid by customer, not donor funds, to kickstart replication

Success factor	Critical issues	Recommended action for transfer to SSA
	Awareness	Highlight the central importance of economic viability; all other parameters determine this critical factor
4. Appropriate and reliable technology	Complexity	Incorporate simple automation for controlling the gas: air ratio to the engine, or for back-flushing bag filters in case of significant pressure drop
	Simplicity	Equip installations with simple devices that do not require a lot of attention, frequent maintenance or replacement of parts
	Import technology	Guarantee technology support, with a local branch and workshop (strongly recommended)
	Cumbersome operation	Incorporate simple automation devices for remote control operation
	Disposal scrubbing water and solid filter material	Try to use dry gas cleaning to avoid toxic liquid wastes; avoid solid filter materials like sawdust or charcoal, as they result in pressure drop over time, and thus reduced efficiency and lower power output
	Awareness	Consider the entire technology chain from feedstock through to heat and power demand
5. Realistic business plan	Viable feasibility study	Include financial, technical and socio-environmental aspects, as well as a sensitivity analysis
	Optimistic forecasting	Adopt conservation figures on feedstock supply, energy demand, operating hours and O&M
	Lack of support	Ensure a critical mass of support from stakeholders at different levels: permitting, contracting, technical, training, knowledge, organisational, marketing, etc
	Ownership aspects	Establish clarity on who will be operator, biomass provider and energy consumer
	Role of project developer	Ensure that project developers sustain their involvement after installation, in case of problems and to improve based on lessons learned
	Awareness	Include not only finance for hardware, but also a substantial top-up allowance for training, education, promotion and knowledge
6. Technology supplier support	Ensure the scope of service	Quantify what is included regarding after-sales service, spare-parts and (re-)training of operators
	Turnkey supplier	Ensure one supplier is responsible for equipment guarantees
	Local support of imported technology	Ensure that foreign suppliers have a local service agent or branch with workshop for repairs and spares
	Local manufacturing	Increase technical and institutional capacity for local or regional manufacture
	Awareness	As gasifiers are complex ensure technical support throughout the project lifetime
7. Sufficient operator skills	Complexity of operation	Provide operating staff with theoretical as well as practical training in O&M procedures; provide an O&M manual in the language of the operators
	Level of automation	Ensure that any automation suits the know-how, experience and qualifications of the local staff
	Imported technology	Limit the involvement of new and unknown components that are difficult to operate and maintain
	Motivation	Provide good salaries and a stake in the project, to minimise staff turnover
	Awareness	Ensure sufficient skills to avoid poor plant performance, with numerous negative consequences

6 Conclusions for gasification development in SSA

6.1 Summary of findings

Research under this study has revealed that small-scale gasification is a bioenergy technology with a disappointing track record in SSA and there is no plant currently believed to be in full operation. There are a few private installations, but the vast majority have been set up with international development finance and have shown mixed and generally poor results. Tanzania and Uganda have the highest number of units, with rice husk or maize cobs the usual feedstock.

The global track record of small-scale gasification has been similarly inconsistent over the last few decades. The sector was initially catalysed by rising oil prices and later by global warming concerns and an energy transition toward renewables. Gasification has been most widely adopted in India and Germany. The development of gasifier programmes or projects over the last 30 years has been supported by governments and development agencies through grant, loan or subsidy, either direct or indirect.

The study has identified two main markets for small-scale gasification in SSA: rural electrification of villages and peri-urban areas, and captive power plants for small-scale industries. In both cases, gasification is a replacement for diesel generators, owing to the lack of grid connection or other affordable alternatives. While gasifiers can also generate heat for industrial processes, this is not a commercially competitive option at the sub-5 MW BSEAA-2 target scale.

Gasification is often considered attractive at small-scale as it is more efficient than direct combustion. But efficiency is only one part of the commercial story, and factors such as the need for more complex and expensive technology, the absence of economies of scale in the gasification industry and the lack of technical capacity to operate and maintain equipment may all conspire to make the whole package uncompetitive. Taken together with observations from numerous plants around the world over the last 40 years, it seems likely that the thermochemical processes involved in biomass gasification are too inherently complicated to be commercially competitive with combustion-based technology or other renewables. This is borne out by the fact that gasification has been around since the 19th century, yet still requires subsidy.

For successful deployment of small-scale biomass gasification, the following seven factors are known to be critical:

1. Consistent and affordable feedstock supply
2. Continuous and sufficient local energy demand
3. Economic competitiveness with alternatives energy sources
4. Appropriate and reliable technology
5. Realistic business plan
6. Technology supplier support
7. Sufficient operator skills

While most of these factors may be applicable to other renewable energy options, the second and fourth points are absolutely critical for gasification, because gasifiers must be run at or near their maximum rating and on a continuous basis; and because gasifiers convert biomass into a gas that then needs substantial cleaning and upgrading, which may only be achievable in an industrial setting or with appropriate scientific and engineering support.

The high failure rates seen in SSA can be attributed to the following factors:

- Downdraft gasifiers are most appropriate for small-scale use, as this design delivers the lowest gas tar levels. However, the feeding systems and reactor designs for these gasifiers demand strict adherence to feedstock specifications. This is either not well-understood or overlooked, especially as operators take liberties with O&M procedures as time goes on, and because plant managers procure cheaper feedstocks to achieve profitability.
- Under-loading of the system or wide load fluctuations result in poor gas quality with reduced calorific value and high tar content, which in turn lowers efficiency, contaminates water and blocks filters.

- There are no gasifier manufacturers in SSA, so all technology is imported. This restricts access to spares, technical guidance and refresher training. Manufacturers are rarely actively invested in the projects and do not have a local representation. Project ownership is further undermined because most installations are donor-funded.
- Technology suppliers are reluctant to be transparent on the limitations and failures of gasification, and incorrect claims may persist longer than for other technologies, due to limited exposure.
- Operating a gasifier installation is complex and requires dedicated, skilled technicians and adequate manufacturer back-up. For various reasons, there is often an absence of such motivated personnel at projects in SSA.
- All stakeholders - from the feedstock suppliers to the end-consumer - must be involved, by giving them an essential role and stake in the project to ensure their commitment.
- These factors come together to affect the economics of small-scale gasifiers, which is the ultimate determining factor in their commercial viability.

6.2 Conditions for successful deployment in SSA

This study has analysed the many reasons for the failure of small-scale biomass gasification initiatives in SSA and globally. It has revealed that small-scale biomass gasification has largely failed in Africa, South America, South Asia and Southeast Asia, because it is not possible to simultaneously satisfy the seven 'success factors'.

Gasification has seen limited success in some European situations with the following provisions:

- High grade feedstock of consistent quality and quantity, usually wood chip or pellets;
- Consistent demand for heat and power, for high working hours under maximum loading;
- Full automation and remote control; and
- Financial incentives, including Feed-in-Tariffs and Renewable Heat Obligations.

These provisions have not been achieved in SSA and it is highly doubtful whether they can ever be established, especially as power grids are expanding rapidly to reach unserved consumers. Drawing also upon worldwide gasification experiences from the past 40 years, this gives no room for optimism that small-scale gasification can be a commercially viable technology for SSA.

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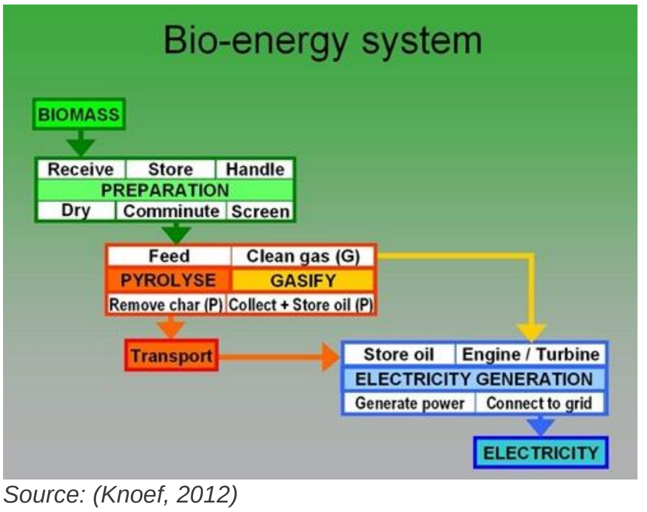
Annex 1: Principles of biomass gasification

This Annex explains some of the principles of gasification, which can aid in understanding the content of the report (Kaupp & Goss, 1984; Knoef, 2005, 2012).

Bioenergy flow in gasification

The complete chain from biomass to power production in a gasification system is summarised in Figure 4.

Figure 4. The bioenergy system



Source: (Knoef, 2012)

Reactor designs

Gasifiers can be classified in different ways:

(a) According to the gasification agent:
- Air-blown gasifiers
- Oxygen gasifiers
- Steam gasifiers

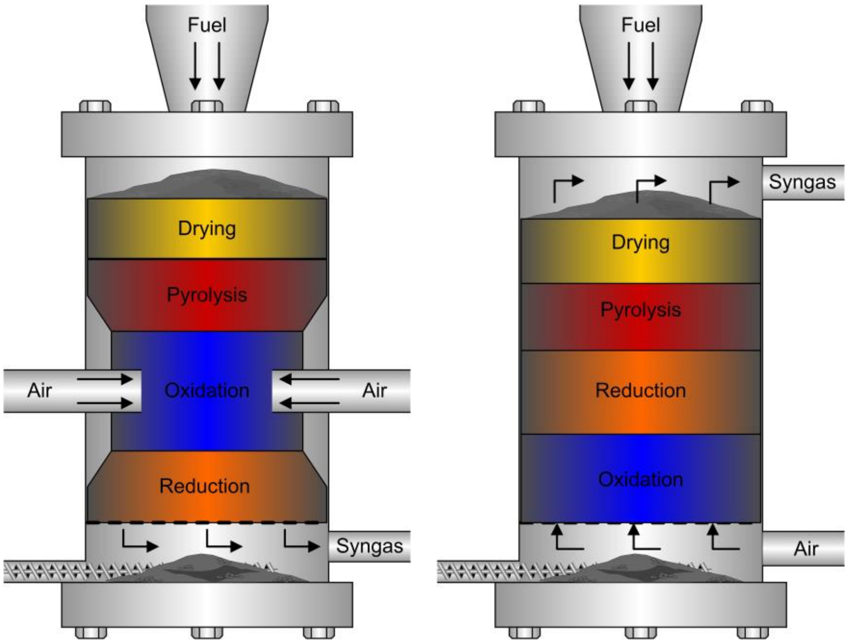
(b) According to the gasification heat source:
- Autothermal or direct gasifiers: heat is provided by partial combustion of the biomass
- Allothermal or indirect gasifiers: heat is supplied from an external source through a heat exchanger or indirect process, i.e. separation of gasification and combustion zone

(c) According to the pressure in the gasifier:
- Atmospheric
- Pressurised

(d) According to the reactor design:
- Fixed bed
- Fluidized bed
- Entrained flow
- Twin-bed

The most common configurations for small-scale installations are the updraft or downdraft autothermal, atmospheric pressure, fixed-bed gasifier (Figure 5).

Figure 5. Downdraft and updraft versions of fixed bed gasifier



Source: (Knoef, 2012)

In a downdraft reactor, biomass is fed at the top and air intake is also at the top or from the sides. The gas leaves at the bottom of the reactor, so the fuel and the gas move in the same direction. The same zones can be distinguished in the updraft gasifier, although the order is somewhat different. Downdraft gasifiers produce lower levels of tar and are therefore the preferred option for engine applications.

It is difficult to scale up this type of gasifier. Under low loading, the reactor temperature decreases and more tars are produced, because tar cracking becomes less efficient. On the plus side, there is lower entrainment of particles in the gas. Meanwhile at high load levels, tar cracking capability is higher, but there are more particles in the gas. At extreme loads, the residence time for tar cracking becomes too short and this increases both the tar and particle levels again. In practice, tar-free gas is seldom (if ever) achieved over the whole operating range of this type of equipment.

The V-shaped throat in downdraft gasifiers (see Figure 5) was invented by the Frenchman Jacques Imbert in the 1920s (Kaupp & Goss, 1984). The throat plays a crucial role in reducing tar content. Air is introduced just above the throat, which creates temperatures above 1,000°C in the combustion zone. A well-designed throat creates a uniform temperature over its whole cross section, sufficient to yield complete cracking of all tars passing through the throat.

Optimal gasification feedstock properties

Each type of biomass has specific properties that determine its performance as a fuel in gasification plants. The most important properties for gasification are as follows (Beenackers & Bridgwater, 1989):

1. **Moisture content.** Dry feedstock produces higher quality gas with a higher heating value and lower tar level. Waste heat from the engine/turbine can be used to dry the feedstock.

2. **Ash content and ash composition.** Ash content in biomass feedstocks varies widely (from 0.1% for wood to 15% for some agricultural products) and influences the design of the reactor, particularly the ash removal system. The chemical composition of the ash is also important because it affects the melting behaviour of the ash. Ash melting can cause slagging and channel formation in the reactor, which may ultimately block the entire reactor.

3. **Elemental composition.** The elemental composition of the fuel is important with respect to the heating value and the emission levels in almost all applications. For example, Nitrogen (N) and Sulphur (S) become NH_3 and H_2S during gasification, and then (if not removed in the cleaning section) become emitted from the engine in the form of NOx and SOx.

4. **Heating value.** On a dry and ash-free basis, most biomass has a heating value of about 19 MJ/kg. But this can be significantly lower for materials with high silica (ash) content, or which are not properly dried.

5. **Bulk density and morphology.** Bulk density refers to the weight of material per unit of volume. Together with the heating value, this determines the energy density of the feedstock, i.e. the potential energy available per unit of volume. Biomass of low bulk density is expensive to handle, transport and store. Bulk density is also important for the performance of the biomass inside fixed bed reactors: high voidage tends to result in channelling, bridging, incomplete conversion and a reduction in gasifier capacity. Fluid bed gasifiers are more tolerant of bulk density variations, but feeding remains problematic. The bulk density varies widely for biomass feedstock (from 100-1,000 kg/m^3), depending on the mode of delivery (e.g. chips, loose, baled). Bridging and channelling frequently occur in fixed bed gasifiers. This is one of the reasons why fluid bed reactors were applied to biomass. The size and distribution of the biomass are also important in determining the pressure drop over the fuel bed and for satisfactory operation. Uniform particle size and favourable particle properties are important to avoid such problems.

6. **Volatile matter content.** The volatile matter content of biomass materials varies between 50 and 80%. High volatile matter content (especially above 70%) has an impact on tar production. Depending on the gasifier design, the volatiles leave the reactor at low temperatures (updraft gasifiers), at moderate temperatures (fluid bed gasifiers) or pass through a hot incandescent oxidation zone (downdraft gasifiers) where they are thermally cracked.

Figure 6. Typical wood residue at a sawmill, Jambi, Indonesia

Source: From personal database of primary author of this report

There may be a need to pre-treat or pre-process certain types of biomass feedstocks for use as gasifier fuel. The need for a suitable feed preparation system is well known, but unfortunately poorly understood. The degree of pre-treatment depends on the specifics of the gasifier, e.g. capacity and type of reactor.

Operating parameters

Guiding parameters for gasifier operation are summarized in Table 6 and discussed further below.

Table 6. Typical values of gasification parameters

Parameter	Unit	Typical value
Specific gas production	Nm^3/kg	2 - 3
Specific gas production	Nm^3/kW$_e$	2 - 3
Specific fuel consumption	kg/kW$_e$	1 - 1.3
Gasifier cold gas efficiency	%	70 - 80
Gasifier hot gas efficiency	%	85 - 95
Equivalence ratio*	-	0.25
Specific load	kg/m^2.hr	500 – 2,000
Turndown ratio	-	2 - 3

* Equivalence ratio is the oxygen used relative to the amount required for complete combustion.
Source: (Knoef, 2005)

Consequences of load variation

Many gasifiers are operated at much lower loads than their rated capacity. This has important implications as the gasification temperatures and specific gas load in the reactor will then be lower than intended, resulting in high tar levels and low particle levels in the gas. The relationship between load level (actual power output against the maximum rated power output) and the level of tar and entrained particles is summarised in Table 7.

Table 7. Tar and particulate content as function of load level

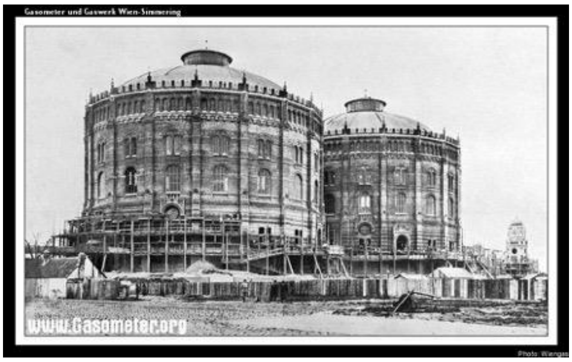
Load level	Tar content	Particulate content
High	Low	High
Low	High	Low

Source: (Knoef, 2005)

One way to avoid gasifiers operating on capacities that are too low is to make use of a parasitic load, like the 25 kW_e installation in Vanuatu (see Annex 6). In this case, when the load dropped below 15 kW_e, power was diverted to a water heater to sustain the load. This approach maintains gas quality, though obviously requires more feedstock.

Another way to cope with load variation is to sustain high gas output but to store the gas for later use. Gas storage in watertight vessels was practised in the past when combustible gas was first produced to be used, for instance, for street lighting. This was abandoned, however, due to the high risk of explosion. Some Chinese suppliers still use gas storage buffers of 5 to 10 m^3 to avoid fluctuations in gas consumption.

Figure 7. Gas storage tanks (early 1900s)



Source: (Knoef, 2005)

Tar production

Tom Reed, a gasification guru from the US, offers the following insight on the tar problem (Milne et al., 1998):

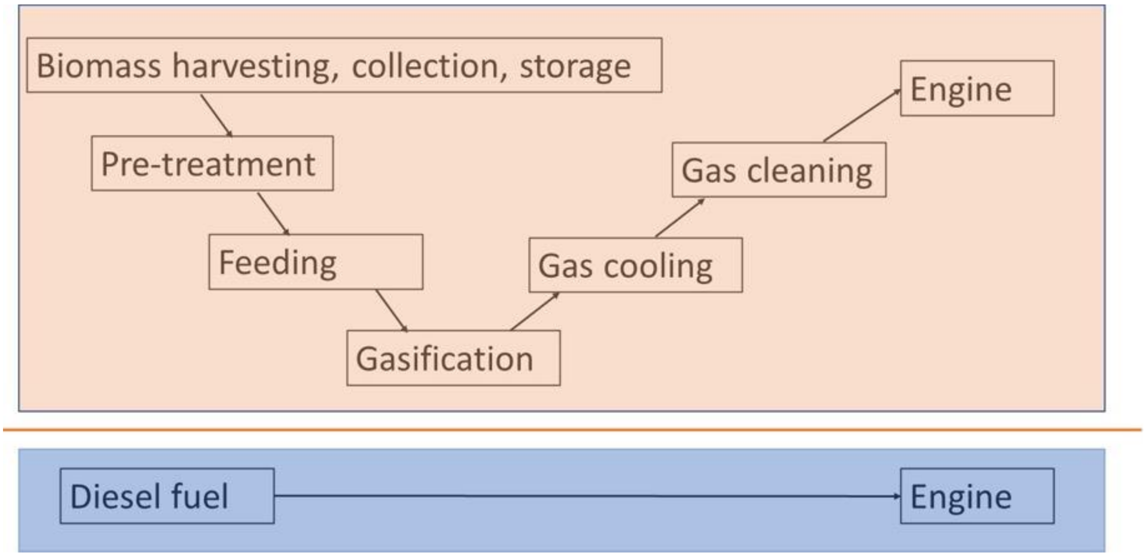
> "*While a great deal of time and money has been spent on biomass gasification in the last two decades, there are very few truly commercial gasifiers, operating without government support or subsidies, day in, day out, generating useful gas from biomass. The typical project starts with new ideas, announcements at meetings, construction of the new gasifier. Then it is found that the gas contains 0.1-10% 'tars.' The rest of the time and money is spent trying to solve this problem. Most of the gasifier projects then quietly disappear. In some cases, the cost of cleaning up the experimental site exceeds the cost of the project! Thus 'tars' can be considered the Achilles heel of biomass gasification. (In the gasification of coal, a more mature technology, the 'tars' (benzene, toluene, xylene, coal tar) are useful fuels and chemicals. The oxygenated 'tars' from biomass have only minor use. With current environmental and health concerns, we can no longer afford to relegate 'tars' to the nearest dump or stream.*"

Complexity of biomass gasification

This report identifies two main markets for small-scale gasification: (1) captive power for small-scale industries and (2) electrification of villages and peri-urban areas. In both cases, these users would otherwise depend largely on diesel generators, owing to the lack of grid connection or unreliability of grid supply.[4]

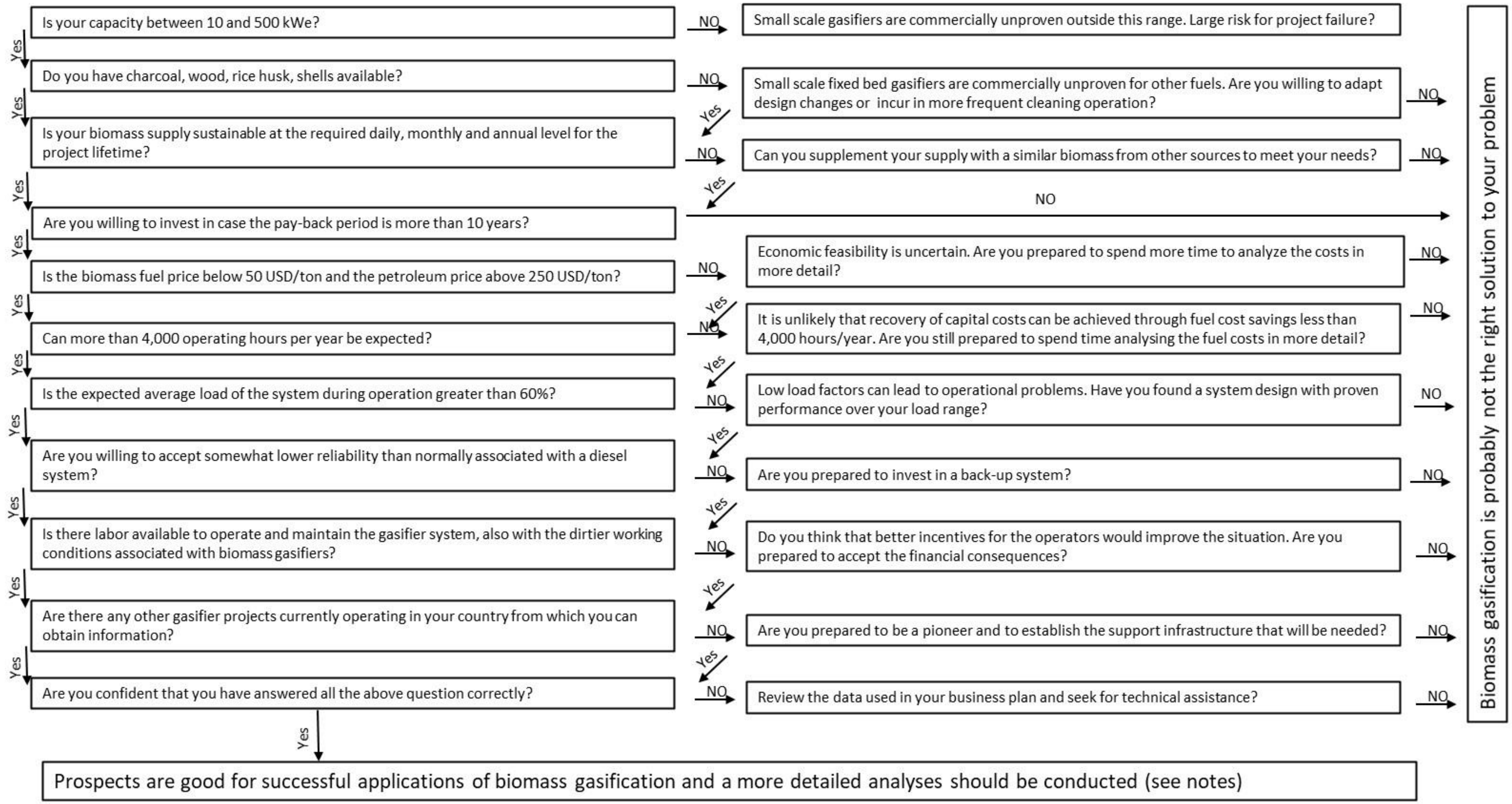
Figure 8 shows the relatively complex configuration of a biomass gasification plant (orange) compared to a simple diesel-genset (blue) which is able to produce the same power. It is clear that much more process stages are involved in a gasification plant.

Figure 8. Process steps involved in biomass gasification compared to a diesel genset



[4] Solar power is not considered a competing technology as solar energy is only of interest up to 5 to 10 kW_e due to battery storage requirements, which is the lowest scale for biomass gasifiers.

Annex 2: Decision matrix for gasification assessment



Source: (H Stassen, 1995)

Notes:

- Small-scale gasifiers commonly have a fixed-bed design. Their typical capacity range is 10-100 kW_e, to a maximum of 500 kW_e.
- Charcoal, dry wood chips/pellets, rice husk and coconut shells are the only fuels that are uniform and can be used directly without pre-processing. Charcoal is preferred as it does not produce any tars, which is the main problem in gasification.
- Sufficient quantity of required quality feedstock is needed over the lifetime of the plant.
- Investment must be reasonably low to compete with alternatives. This can be expressed in many ways, perhaps as a maximum payback period.
- Fuel costs, operating time and load factor are important local conditions. Load factor is defined as the average load divided by the peak load in a specified time period. Low load factors affect income generation and have undesirable technical impacts as more tars are produced and the gas heating value decreases, due to a drop in reactor temperature.
- Adding a complex biomass gasifier to an existing diesel engine is an intrinsic reason for lower reliability.
- Gasification is more labour intensive and cumbersome than a diesel power plant or solar PV, and requires a more skilled, motivated and disciplined operator.
- Learning from the experience of other installations, negative or positive, is important to decide which technology is appropriate for the local situation.
- This decision matrix is only a pre-screening tool. If all questions are answered positively, there are good prospects for a successful project. In case of a positive outcome, a more detailed technical-economic feasibility study can be conducted, followed by the other phases of a typical project cycle.

Annex 3: Gasification projects in SSA

Country	Location	Owner	Manufacturer	Project developer	Financed by	Operational?[5]	Details
Ethiopia	Addis Ababa	MOWIE	Unknown	Unknown	Norwegian funds	No	Experimental
Ethiopia	Unknown	Solaria Trading	Unknown	Solaria Trading	Climate Innovation Centre	No	Only feasibility study
Ghana	Asueyi, Techniman Municipality, Brong Ahafo Region	Zoomlion Ghana Ltd	Ankur	Root and Tuber Improvement Project	IFAD	No	Personnel left
Ghana	Papasi, Offinso North District	Community	All Power Labs, USA	Kumasi Institute for Tropical Agriculture	USADF Power Africa	No	Technical problems
Kenya	Elburgon	Timsales	Fengyu, China	Unknown	Industry	No	To be confirmed by owner
Kenya	Marigat, Baringo County	Cummins Cogeneration	Biogen, Dominican Republic	Cummins Kenya	AECF REACT (feedstock supply)	No	Technical problems, gas cleaning
Kenya	Turkwel, Turkana County	Turkana Basin Institute	All Power Labs	Turkana Basin Institute	Own funds	No	Technical problems
Mozambique	Titimane, Cumba District, Niassa Province	SAN-JFS	All Power Labs	SAN-JFS	EEP	No	Licensing issues. Grid arrival
Nigeria	Ohaukwu, Ebonyi State	cooperative	IISc Bangalore	UNIDO	UNIDO	No	Functional but not commercially operated
South Africa	18 sites	Innov8 Africa and Black Swan Group	Carbo Consult	Industry	Unknown	No	Company no longer active
South Africa	Greater Tzaneen Municipality, Limpopo	Agatha Sawmill	Carbo Consult	Marawasi Consulting Services	Sawmill	No	Only feasibility study
South Africa	Johannesburg, Gauteng	Unknown	Powermax	Unknown	Unknown	No	Tar problems

[5] Operational in this context implies that the gasification plant is operated on a regular, commercial basis, and not for demonstration only.

Country	Location	Owner	Manufacturer	Project developer	Financed by	Operational?[5]	Details
South Africa	Limpopo	Sawmill	Recor	Recor	Industry	Unknown	To be confirmed. Possible to visit according to Recor
South Africa	Melani Village, Eastern Cape	Eskom	Carbo Consult	University of Fort Hare	Eskom	No	To be confirmed by owner
South Africa	Nampo Village	Sawmill	Recor	Recor	Industry	No	To be confirmed by owner
South Africa	Graskop, Mpumulanga	Sawmill	Fengyu	Unknown	South Africa Sherpa Trade and Invest 76	No	Owner stopped business
Tanzania	Biro village, Kilombero District, Morogoro Region	TaTEDO (NGO)	Husk Power	ONGAWA Engineering	EEP	No	Intermittent, income problems
Tanzania	Cashew producing area	Small Industries Development Organisation (Parastatal)	TERI	Unknown	UNIDO	No	Waiting for EIA study
Tanzania	Kibindu, Coast Region	TaTEDO	Husk Power	TaTEDO/Sescom	Power Africa	No	Only solar power is used
Tanzania	Magungumka, Singida Region	Ageco	Husk Power	Ageco	Power Africa	No	Awaiting custom clearance
Tanzania	Mbaha and Lituhi villages, Nyasa, Ruvuma Region	Unknown	Husk Power	Wananchi Power Providers	UNIDO GEF	Possibly	2 of 5 units in operation,
Tanzania	Mbeya Region	Space Engineering Comp.	Ankur	Space Engineering	Day Ouwens Fund	No	Demand too low; not economical
Tanzania	Mngeta, Kilombero District	Kilombero Plantations Ltd	Fengyu	Kilombero Plantations Ltd	Plantation	No	Feedstock shortage. Grid arrival. Company closure.
Tanzania	Mtwango village, Iringa Region	Unknown	Unknown	Redcot	UNIDO	No	On hold, grid arrival
Tanzania	Nyakagomba village, Geita district	Unknown	Husk Power	Nishati Associates	EEP	No	Grid arrival, plan for relocation

Country	Location	Owner	Manufacturer	Project developer	Financed by	Operational?[5]	Details
Tanzania	Zombo community, Malalo, Kilosa District, Morogoro	Ruaha Energy	Husk Power	Ruaha Energy	EEP	No	Never went ahead. Not feasible
Tanzania	Mvuha Village. Morogoro Rural District, Morogoro Region	Unknown	Husk Power	Husk Power (own venture)	Unknown	No	Funding problems
Uganda	Kayinja Landing, Lake George, Kamwenge District	Unknown	Husk Power	Pamoja Cleantech	EEP	Unknown	To be confirmed by owner
Uganda	Magala village, Ssekanyonyi, Mityana District	Sawmill	Husk Power	Pamoja Cleantech	Nordic Climate Facility	No	Demand too low; not economical
Uganda	Masindi	Nyabyeya Forestry College	Husk Power	Nyabyeya Forestry College	Unknown	No	Demand too low; not economical
Uganda	Mukono	Farm	Ankur	Kaesenge Electricity Power	DED (Germany)	No	Decommissioned after owner left
Uganda	Muzizi, Kibale District	James Finlay	Ankur	James Finlay	Estate	No	Grid arrival; technical problems
Uganda	Opit Youth Training Centre, Gulu District	CREEC, Makerere university.	All Power Labs replaced by Ankur dual fuel gasifier	Pamoja Cleantech	World Bank, UNIDO	No	Technical problems
Uganda	Tiribogo, Mpigi District	50% REBi, 50% Pamoja Energy	Husk Power	Pamoja Cleantech	Nordic Climate Facility	No	No commercial model
Uganda	Unknown forestry plantation	Unknown	Entrade	Entrade	USPDA	No	Not feasible
Zambia	Kaputa	Unknown	Unknown	UNIDO	GEF, UNIDO, UNEP	No	Grid connection, feedstock supply problems

Source: Project developers, technology providers, Industry informants and secondary data sources.

Note: From the ten BSEAA-2 countries, no gasification projects were identified in Rwanda

Annex 4: People consulted

First name	Last name	Function	Organisation	Country
Vincent L	Mughwai	Managing Director	AGECO Energy	Tanzania
Tom	Price	Manager	All Power Labs	Canada
Ashok	Chaudhuri	Sr. General Manager, Business Development	Ankur Scientific Energy Technologies	India
Mawulolo	Amouzou-Glikpa	Administrative Director (formerly Novis technician for bioenergy projects in W. Africa)	Avenir Solaire	Senegal
Harald	Gottschalk	Manager	Burkhardt	Germany
Joshua	Ogwok	Bioenergy engineer	Centre for Research in Energy and Energy Conservation (CREEC)	Uganda
Bernadette	Shalumbu	Project coordinator	Desert Research Foundation of Namibia	Namibia
Henny	Romijn	Assistant Professor	Eindhoven University of Technology	Netherlands
Fred	Eklund	Portfolio Coordinator	Energy and Environment Partnership for Southern and East Africa (EEP)	Finland
Lauri	Tuomaala	Head of Portfolio and Finance		South Africa
Wim Jonker	Klunne	Former Programme Director, KPMG Finland		
N.S.	Mamphweli	Contact person	Eskom	South Africa
Michael	Jiang	Manager	Fengyu Group	China
Hugo	Douglas-Dufresne	Engineering Director	Finlays Tea	Kenya
Adriaan	Mol	Project Manager	Husk Power Systems	Tanzania
Henry	Mungure	Country Operations Manager		
S.	Dasappa	Professor	IISc Bangalore	India
John	Kiragu	former Power Manager	Kilombero Plantations Ltd	Tanzania
Benjamin	Boahen	Researcher	Kwame Nkrumah Univ. of Science & Technology	Ghana
Raymond	Lumansi	Technical Manager (formerly Pamoja Cleantech)	Mandulis Energy	Uganda
Thomas	Helle	CEO	Novis	Germany
	Lily	Manager	Powermax	China
Noel	Guy	Senior Technical Support Engineer	Recor	South Africa
Skukuru	Meena	Manager	Sescom	Tanzania
Shima	Sago	Manager		
Moiz Abbas	Nazerali	Managing Director	Solaria Trading	Ethiopia
Peter & Philip	Mtui	Co-founders	Space Engineering	Tanzania
Matthias v.	Senfft	CEO	Spanner Re2	Germany
Tom	Miles	President	T R Miles Technical Consultants	USA

Leland T.	Taylor	Group CEO	Thermogenics Inc.	USA
Victor	Akim	Project Manager	UNIDO	Tanzania
Victor	Béguerie	Project Manager		Madagascar
Kevin	Blanchard	Project Manager		
Tom	Coogan	Project Manager	United States African Development Foundation/Diligent Consulting	Tanzania
Regan	Bernard	Regional Financial Officer		
Claudia	Schwartz	Energy Access Advisor	USAID	USA

Additional experts and project developers were contacted but did not respond, including:

- Husk Power Systems, India (technology suppliers and project developers; local staff in Tanzania were responsive, however)
- David Muñoz, Technical advisor to gasification project in Kilombero
- UNIDO Projects, Ebonyi State Government, Nigeria (gasifier project in Ebonyi State)
- Carbo Consult, South Africa (developers of up to 20 sites in South Africa)
- Pamoja Cleantech, Sweden (developers of several projects in Uganda)
- Cummins Cogeneration, Kenya (developers of a large-scale project at Marigat)
- Biogen, Dominican Republic (technology suppliers to Communis Co-Gen, Kenya)
- Ruaha Energy Company, Tanzania (developers of project using EEP funds in Tanzania)

Annex 5: Additional information on gasification experiences in Europe

Introduction

This Annex provides some background information on experiences with gasification in European countries.

The key drivers for biomass gasification were the oil crisis of the 1970s and 1980s, followed by the introduction of subsidies for renewable energy, including FiTs and Renewable Heat Obligations. Several countries developed policies to support the market for energy from renewables, including biomass. It is these countries, and especially those with paper industries processing wood, where the development of biomass gasification has become most developed. This includes Finland, Sweden and the USA. Denmark has meanwhile had a long tradition of support for renewables, joined more recently by countries such as Germany, Belgium, the Netherlands, Austria, Italy and the UK. This widening support opened up new markets and thus the scope for more efficient and innovative technologies, such as biomass gasification (Babu, 2005; Hrbek, 2016; Knoef & Kwant, 2004; Kumar et al., 2009).

Some successful companies and installations are described below, to determine the critical success factors, lessons learned and potential for transfer to SSA.

Cofiring power stations with a gasifier

The first gasifier installed at a power station was in Zeltweg, Austria, followed by others in Lahti, Finland; Amer, the Netherlands; Vermont, USA; and Ruien, Belgium. Despite successful operation, the plant in Austria was closed because the power station was shut down. The Vermont project was successfully completed, but never operated, because of the low availability of the power plant. The Lahti gasifier is still in operation. A new type of gasifier became operational at Ruien.

The details and status of these plants is summarised in Table 8. They are all fed with contaminated wood waste. In this co-firing concept, the (wood) ash from the gasifier is not mixed with the ash from the coal firing, which is very important as the coal ash is sold.

Table 8. Cofiring gasifiers

Location	Gasifier type	Capacity (MW_{th})	Status
Zeltweg, Austria	CFB*, fed directly into pulverised coal boiler	10	Operated 1998 to 2001
Lahti, Finland	Foster Wheeler CFB, fed directly into pulverized coal boiler	60	Operational since 1998. Gas cleaning upgraded.
Amer, Netherlands	Lurgi CFB, with gas cleaning and ammonia removal, into pulverized coal boiler	80	Operational since 2000. Gas cleaning modified 2004.
Vermont, USA	Ferco Silvagas (Batelle) gasifier, planned to install combined cycle (steam and gas turbine)	60	First test runs 2000. Demonstration project finished
Ruien, Belgium	CFB, Foster Wheeler, fed directly into pulverized coal boiler	50	Operational since May 2003

** CFB – Circulating Fluidized Bed*

Source: (Babu, 2005)

Figure 9. Gasifiers at Lathi, Finland and Amer, the Netherlands

Source: (Knoef, 2005)

Heat gasifiers

With heat gasifiers, the main aim is to produce heat for industrial or residential use (whereas in co-firing gasifiers, part of the coal feedstock is replaced by biomass to produce both heat and power). There are commercially manufactured heat gasifiers available. The most well-known are those of Bioneer (fixed-bed, updraft), PRM Energy (fixed-bed, updraft), Ahlstrom (now Foster Wheeler) and Lurgi Umwelt (both CFB). Around ten Bioneer gasifiers have been in operation successfully for a number of years in Finland and Sweden. In most cases the gas is used for combustion in boilers and for district heating. Less well-known are the small-scale heat gasifiers installed in developing countries supplying heat for lime kilns and tea drying.

Figure 10. Bioneer heat gasifier (left) and Waterwide heat gasifier in Rajamandala, Indonesia

Source: (Knoef, 2005)

Integrated gasification and combined cycle gasifiers

The oil crises prompted interest in large-scale gasification technology. In 1991, the first pressurized Integrated Gasification Combined Cycle (IGCC) biomass gasifier was constructed in Värnamo, Sweden, using technology from Foster Wheeler. The European Commission saw the potential of this technology and called for proposals for THERMIE targeted projects in 1993 (Pitcher et al., 1998). Three projects were selected: Arbre (UK), Bioflow (Denmark) and Bioelettrica (Italy). Arbre was based on TPS (Sweden) technology and was installed and commissions. However, the owner (Kelda Group) sold the plant to EPRI in 2002 and the project was mothballed shortly thereafter. The Energy Farm project from Bioelettrica faced many technical and non-technical problems. The selected atmospheric gasification technology from Lurgi was changed to a pressurized gasification technology from Carbona, but the project was finally terminated in 2003. The Bioflow project never left the engineering stage.

The Värnamo plant was also mothballed despite positive results from the demonstration project. The capacity proved too small for commercial operation. Within the 6th EU framework program, an integrated project called CHRISGAS was approved for syngas production using the Värnamo gasifier.

Figure 11. Arbre gasifier, UK and Värnamo plant, Sweden

Source: (Knoef, 2005)

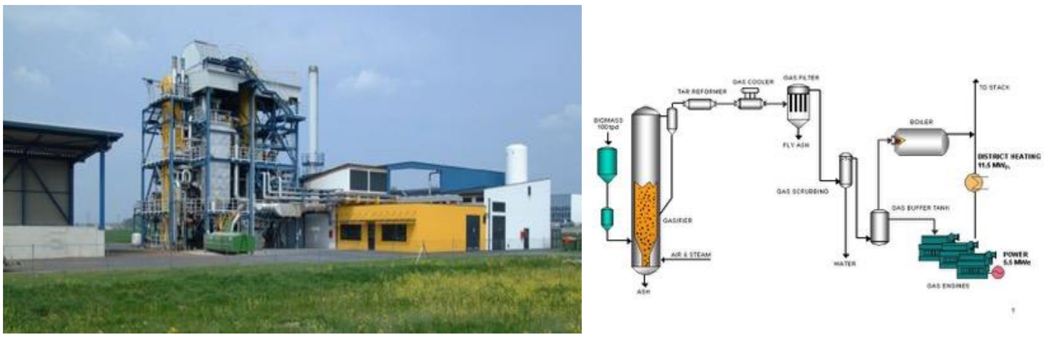
Circulating fluid bed gasifier with gas engine

A relatively new application is the combination of CFB technology coupled with gas engines. Two main examples of this combination have been developed:

1. Fast internal circulating fluidized bed (FICFB) technology developed by TU Vienna. The first 2 MW_e gasifier went into operation in Güssing, Austria. Güssing is a small town of around 4,000 inhabitants close to the Hungarian border. The region was very poor until biomass was tapped into as source of energy. With the installation of the CHP plant in 2000, the whole town could be supplied with green electricity and heat from biomass. The plant cost €9 million with 60% public funds (EU, national) and 40% private investment. Based on the same technology, further FICFB plants were built in Oberwart, Senden (Germany), Gothenburg (Sweden), Burgeis (Italy) and Gaya (France).
2. The Carbona CFB 4 MW_e gasifier in Skive, Denmark with a catalysis gas cleaning system and a gas engine.

Both installations were backed-up with national funding and expertise from technical universities. They acted as demonstration projects for introducing more efficient medium-scale CHP district heating systems based on biomass gasification, also partly accelerated by new favourable legislation like FiTs and dedicated emission standards for biomass gasifiers.

Figure 12. FICFB gasifier at Güssing, Austria and Carbona gasifier at Skive, Denmark



Source: (Knoef, 2005)

Fixed bed gasification for power production

A large number of small-scale, fixed bed gasifiers are either in operation or under development, of which some are based on old technologies (e.g. Northern Ireland, Harboøre) and others are implementing more advanced technologies from recent R&D (e.g. electrostatic precipitators, tar crackers, 2-stage gasifiers). Most of the units are CHP plants where heat is used for district heating. In India and China alone, hundreds of gasifiers are in operation at farms and small industries to produce heat or electricity at a local level. Countries with favourable FiTs for electricity and 'green heat' regulations have the most installed gasifiers (Babu, 2005; Böcker-Riese, 2017). Some examples are described below:

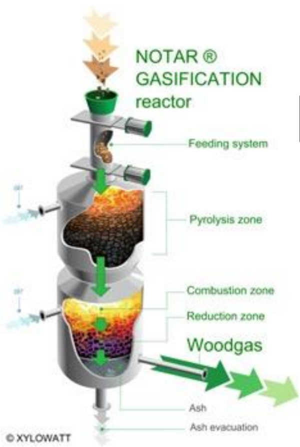
1. The 1.5 MWe Harboøre plant in Denmark was installed in December 1993 for district heating and was optimized for gasification operation until 1996. From 1997 to 2000, a gas cleaning system was developed. In 2000, two Jenbacher gas engines were installed. A cleaning system for tar-contaminated wastewater was developed by 2002. The recovered tar is stored and used in a tar oil-boiler to meet the peak winter load for district heating. The plant has been in commercial operation for 30 years under local ownership by the CHP company, using local feedstock and with local use of the heat and power. The plant cost around €9 million plus indirect costs (e.g. development projects at universities and partners), of which 40% was provided by the Danish Energy Ministry and the remainder by the district heating company. The unit achieves over 7,000 operating hours per year. A second 'Harboøre-type' plant has been installed in Japan. Despite their successful operation, this technology has not been replicated further, probably due to the high initial cost.

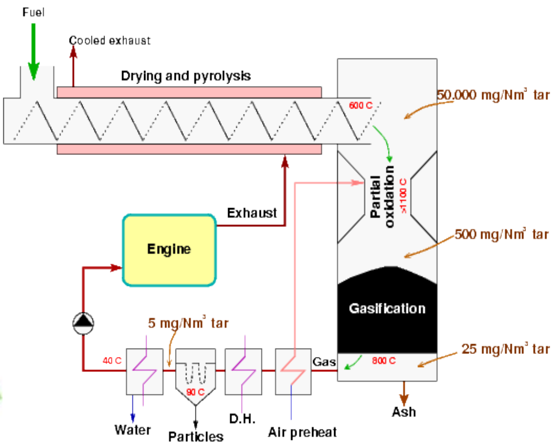
Figure 13. Harboøre gasifier, Denmark

Source: (Knoef, 2005)

2. Xylowatt (Belgium) have installed 600 kW_e downdraft gasifiers at plants in Belgium and France. They claim to have developed a totally tar-free system, the NOTAR gasifier.
3. In Denmark there were two so-called three-stage gasifiers: the Viking gasifier of the Danish Technical University (DTU) and a second design developed by TK-Energy. Despite DTU's technical inputs and the financial support of the Danish government, neither were commercialised, most likely due to their complexity.

Figure 14. NOTAR gasifier (Xylowatt) and Viking gasifier (Danish Technical University)

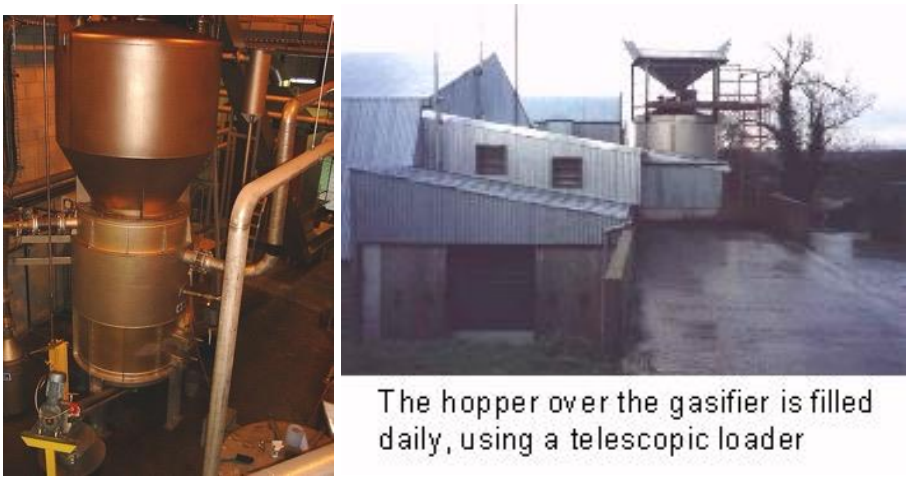




Source: (Knoef, 2005)

4. Rural Generation installed a 100 kW_e downdraft gasifier at Brook Hall Estate in Londonderry, Northern Ireland, which operated partially on energy crops. It operated for about 20,000 hours. Biomass Engineering Ltd (UK) installed several gasifiers at small scale, including a 75 kW_e wood chip gasifier at Ballymena Ecos Centre, also in Northern Ireland.

Figure 15. Ballymena and Brook Hall Estate, Northern Ireland



Source: (Knoef, 2005)

5. Spanner Re^2 GmbH[6], established in 2005, is part of Spanner group and has 56 employees at the company's headquarters in Neufahrn/Landshut, Germany. Spanner Re^2's wood cogeneration plants produce decentralised electricity and heat from wood chips by using a wood gasifier. Depending on the model, the plant generates 30-45 kW_e of power and 80-120 kW_{th} of heat. Wood chip consumption is between 30 and 45 kg/h, giving a consumption of approximately 1 kg of wood chips per kW of electricity output.

   Spanner Re^2's interest in gasification was initiated in part by the introduction of the Erneuerbare-Energien-Gezets (EEG), a German government programme stimulating renewable energy through favourable FiTs. In 2007, the company started a cooperation with Mr. Bernd Joos, who had a long track-record in developing a 'tar-free' gasification concept. He attracted interest in Germany from his long-running wood gasifiers on tractors. Spanner Re^2 selected the Joos technology for its simplicity, close to tar-free wood gas, and fast start-up and shut-down procedure.

   The company's installations consist of a downdraft type gasifier with a relatively large feeding sluice, a heat exchanger, fabric bag filter (which is automatically cleaned by a back-pressure device), and finally a safety filter. The latter blocks the gas flow in case the main bag filter malfunctions. Standardized dry wood chips are used as feedstock with size G30-G40 (Linddana A/S, n.d.), moisture content <15% and fines <30% (grain size <3-4 mm). Heat from the gas cooling is partly used for woodchip drying. No contaminated wastewater is produced. Initially they supplied two versions: 45 kW_e with turbocharger and 30 kW_e without turbocharger.

   Spanner's systems have been installed across Europe, providing heat and power for farms, wood processing industries, supermarkets, hotels, families, villages and community cooperatives. Sales had reached 20 units by 2010 and over 130 units by 2012, and there are now said to be 800 units in operation. According to Spanner RE^2, the critical success factors for their technology are:

   - standardized input material (dry wood chips);
   - only gas dedusting is needed (Spanner claims that the gas contains minimal tar so only dust needs to be removed using a fabric filter);
   - skilled and motivated operator;
   - robust GM 5.7 litre V8 engine with electronic ignition ;
   - intensive operation and service training for operators/customers;
   - long-term experience that has led to many improvements; and

[6] www.spanner.de

- focus on customers with potential for long runtimes of 5,000-8,000 hours/y, to ensure commercial viability.

Figure 16. Compact Spanner gasifier, Germany

Source: Hrbek, J. (2016)

Spanner have installed several installations outside Europe in North America, Central America, South America and Asia. With their HKA 49 model, they intend to deliver their first power plant to Africa in 2020, to be installed in Tanzania and operated with coconut wood chips.

6. Another successful gasifier company is Burkhardt (Germany), established in 1978. They initially sold CHP equipment and started work on gasification in 2004 due to the favourable FiTs, increasing prices of fossil fuels and awareness of climate change. The Burkhardt wood gasifier v.3.90, together with the CHP plants ECO 165 HG (wood gas spark ignition) or ECO 180 HG (wood gas pilot injection), are fuelled with pelletized wood residues. They offer a modular design with only two capacity options (165 and /or 180 kW_e). The gasifier is an updraft gasifier, but the air and the pellets are brought in at the bottom of the reactor. So at the bottom is a pellet layer, then the pyrolysis and oxidation zone, and on top a fluidized coke bed. In this way it is claimed that there is almost no tar. This gas is cooled and particles are filtered with a bag filter. The gas is also dried before it enters the pilot injection engine.

There is no independent measuring report on the performance of the Burkhardt gasifier, but the existence of more than 260 operational units is evidence of its success. Burkhardt has a service team in Ladbergen where 32 gasifiers are in operation and deliver heat to Osnabrück-Münster airport and the adjacent industrial area. An official document from Münsterland Energy GmbH shows an availability of almost 99% for the 32 gasifiers. Drawbacks include the requirement to use costly wood pellets and the need for ignition oil for the engine.

According to the supplier, the most important success factors are:

- no need for tar cleaning - methane concentration is used as indicator for tar and if it exceeds a certain level the gas is burned in a flare;
- standard pelletized fuel with a quality ENplus A1 or in accordance with ISO 17225-2;
- Serial production of a standard/modular design;
- Internet access for remote control and automatic operation; and
- Interested operator with excellent electrical and mechanical knowledge.

According to the manager, Burkhardt has no interest in supplying installations in SSA due to the strict feedstock requirements, which cannot currently be met. Moreover, they would have to organize personnel, service support and spares supply, which they are not in a position to do.

Figure 17. Compact Burkhardt gasifier, Germany

Source: Hrbek, J. (2016)

A typical success story for small scale biomass gasification using the Burkhardt technology comes from a sawmill owner in a mountainous rural area near a village with 3,000 inhabitants, surrounded by farmland and forest. With the waste wood from the sawmill and a wood processing facility, he was supplying a small district heating system with a biomass boiler. He upgraded the capacity of this system with a CHP gasifier unit. The thermal power output of the gasifier was chosen to cover the year-round baseload of the district heating grid, so as to maximise the full load running hour of the gasifier (which runs for at least 7,500 hours/year). So the sawmill owner's waste problem became fuel input for the CHP unit, with a rating of 280 kW_{th} and 140 kW_e. The unit supplies electricity to the factory and low temperature heat for fuel conditioning. The gasifier is automated and sawmill staff are able to handle basic O&M.

Lessons from Europe experiences

1. Successful gasifier plants use standardised technology of modular design, allowing for serial production.
2. The client must usually have access to their own wood resources. It is also possible to buy woodchips following objectively defined standards.
3. Depending on the design, each technology needs a standardised wood fuel (either wood chips or pellets). Drying of the wood fuel can be provided by the gasifier installation.
4. With the exception of a few plants like Harboøre, all gasifiers use a dry gas cleaning system producing no contaminated liquid effluent. This is a major environmental benefit over systems that use scrubbers for gas cleaning. Some installations produce condensate during cooling just before the engine (where the gas is mixed with air), but this condensate is relatively clean and in small amounts.
5. Plants with a high availability and long-term experience permit the incorporation of minor improvements and fine-tuning. These improvements are not possible when operating experience is very limited.
6. Labour costs are high in Europe but can be offset by full automation and remote control. One person can potentially manage several installations.
7. Several companies and installations have close relationships with academic institutions or R&D centres, to help improve their designs.
8. Long-term continuous operation without interruption provides maximum power and heat, and therefore good economics. Some heat is often used to dry feedstock.
9. Typical investment costs are €4,000-5,000/kW_e and maintenance costs are 3-5 €cents/kWh_e.
10. The projects in Harboøre and Güssing show that new innovations can be developed successfully, given sufficient financial resources and the close support of R&D institutes.
11. Typical customers for small scale CHP are farmers, cluster of houses, wood processing industries, supermarkets and community cooperatives.

Annex 6: Additional information on gasification experiences in selected low- and middle-income countries

This Annex gives additional background information on the two Indian companies who have been most active in SSA (Ankur Scientific and Husk Power), as well as selected experience from case studies in other low- and middle-income countries (Jain, 2000; Kumar et al., 2009; Masera & Faaij, 2014; Muzee, 2012; Quaak et al., 1999; Salam et al., 2010).

Ankur Scientific[7]

Ankur Scientific Energy Technologies has been manufacturing gasifier system for almost four decades, with a focus on woody biomass and rice husk as fuel. They offer three types of gasifiers, each designed for a specific type of fuel. Their gas cleaning system consists of two parallel filter units with a coarse filter (wood chips) and two fine filters (sawdust), to allow constant operation during the cleaning of one filter system. Ankur has exported gasifiers to various countries including Australia, Germany, Italy[8], Cambodia, Malaysia, China, Cuba and the USA, with operational experience from 4 up to 1,000 kW capacity. According to the company manager, more than 95% of their current business is overseas. Around ten units have been installed in SSA, though none of them are in operation as planned. According to Ankur, this is due to local issues rather than any problems with their technology.

Figure 18. 250 kW_e Ankur gasifier in Germany (presented at a conference in Stuttgart 2008) and 500 kW_e gasifier under construction in Cuba

Source: Harrie Knoef personal records

[7] www.ankurscientific.com
[8] The installations in Germany and Italy were shut down shortly after commissioning, due to cumbersome operation and contaminated wastewater.

Husk Power Systems[9]

Figure 19. Husk Power Systems gasifier

Source: From personal database of primary author of this report

Husk Power Systems (HPS) has created proprietary gasifier technology that converts rice husks into electricity. Ganesh Engineering Works (located in Bihar) provides the technology package and HPS installs and operates the gasifiers in the range 25-100 kW_e. HPS also designs multi-fuel gasifiers that can use rice husk, wheat husk, mustard stems, corn cobs and wood chips. Since 2008, the company has installed 80 plants in Bihar alone. Their business model is primarily focused on off-grid villages. Their standard 32 kW plant needs 50 kg of fuel per hour and can power about 700 typical rural households. The group has been supported by several financial institutions. In 2018, HPS received US$20 million from Shell, Swedfund and ENGIE Rassembleurs d'Energies to scale up its renewable mini-grid business in Africa and Asia, providing electricity to villages.[10] The company claims to design, build, own and operate one of the world's lowest-cost hybrid power plant and distribution networks in India and Tanzania, providing 24/7 power. Similar to Ankur, they have installed around ten units in SSA, but none of them are in operation as planned. They are the only foreign company active in SSA, with a local office in Dar es Salaam, Tanzania. It is believed that they have shifted their focus fully to solar PV, however, and they no longer respond to enquiries about their African gasifier projects.

Indian Institute of Science

Figure 20. Open-top Xylowatt gasifier at Bulle, Switzerland, based on IISc technology

Source: (Knoef, 2005)

At the Indian Institute of Science (IISc) Bangalore, an open-top gasifier reactor was designed for using wood chips as fuel. This technology was licensed to several equipment producers. It was also transferred to Switzerland in a co-operative project between the two countries. The technology was offered by Xylowatt SA and one installation was installed in Bulle, Switzerland in 2001. It was not replicated.

Assessment of Indian gasifiers

While a large number of gasifier system have been set up by various Indian manufacturers, there is little information in the public domain on the technical, economic and socio-environmental performance of these systems. Most performance data comes directly from manufacturers, but is generally over-estimated and results often show differences of perception between the technology provider and the end-user (Dasappa et al., 2011; Ghosh et al., 2004).

GTZ commissioned a rapid assessment of gasifiers at six locations in India in 2009 (Energypedia, 2018). All of these medium sized plants seemed to be constantly in use, providing an electricity output of 60 - 500 kW. Rice husk and wood were used as fuel. Plants with diesel engines needed an additional input of 20-30% diesel fuel. Plants with specially designed gas Otto engines worked exclusively with producer gas. However, they needed an additional small electric generator during start-up. All of these plants had a sophisticated gas cleaning system. However, the plants did not come close to meeting European safety and pollution standards for liquid and gaseous emissions.

The World Bank evaluated the Village Energy Security Programme in which several small-scale gasification plants (10-20 kW) were installed in India from 2005 (World Bank, 2011). The findings were "largely mixed" due to:

[9] www.huskpowersystems.com
[10] www.huskpowersystems.com/husk-power-systems-receives-20-million-investment-from-shell-swedfund-engie-rassembleurs-denergies/

- Technology suppliers' failure to provide prompt and reliable after-sales services;
- Inadequate training of local operators;
- Lack of organized supply of fuel wood; and
- Lack of capacity and interest among the village communities to manage the day-to-day affairs of the power plant.

To overcome these problems, the study proposed shifting the management of the power plants from self-organized cooperatives to skilled entrepreneurs, and to establish local service providers duly certified by the equipment manufacturers.

Lessons learned from India

The main difficulties emerging from the Indian experience can be summarized as follows:

1. Technology suppliers' failure to provide prompt and reliable after-sales service;
2. Inadequate training of local operators;
3. Lack of organized supply of fuelwood;
4. Lack of capacities and interest among the village communities to manage the day-to-day affairs of the power plant;
5. Lack of adherence to given fuel specifications by the customer's operating personnel;
6. Frequent change of operating personnel, with plant managers often assuming that operating the plant is straightforward and under-estimating the role of training;
7. A tendency to take liberties with O&M procedures when systems are operating well and according to expectations;
8. The O&M burden of a gasifier when coupled to an existing diesel genset, for which operators expect (financial) incentives;
9. A tendency for customers side to hold the supplier responsible for almost anything, as a new technology is involved and most manufacturers have few installations, experience and customers;
10. Complex feedstock specifications and O&M procedures for small-scale gasifiers;
11. Damage to vital components when feedstock and/or O&M instructions are not strictly adhered to (pointing to a need for training of the operator and commitment of the plant manager);
12. Lack of user-friendliness in design features, both in biomass handling and O&M, in particular with small scale batch-wise units (e.g. poking of the fuel bed, removal of ash, and the handling of char and condensate handling is messy, dirty and laborious work which also poses safety hazards);
13. A conflict for technology developers between the need for intellectual property protection and the need to impart more complete information to the O&M personnel;
14. Reluctance of suppliers and technology developers to tell the whole story to potential customers regarding failures at other sites;
15. Failure of most systems to meet national standards for tar and particulate matter content in the producer gas entering the engine, due to faulty measuring equipment or fluctuating operating load resulting in lower temperatures and poor gas quality, with particularly harmful effects on turbocharged and/ after-cooled engines; and
16. Lack of substantial effort and resources invested by equipment manufacturers in long-term customer relationship building, often because they consider gasification a side business and are rarely an active financial partner in the projects.

Case study 1: SME Renewables in Cambodia

This case study is an example of an attempt to address the high capital costs associated with importing gasifier technology and expertise. Ankur Scientific delivered expertise and knowledge to a newly established company in Cambodia called SME Renewables for local manufacture.

Figure 21. SME Renewables gasifier in Cambodia

Source: From personal database of primary author of this report

After years of civil war, Cambodia suffered from poor basic infrastructure and a low level of rural electrification. Most rural electricity was generated at high cost using diesel. Like other Southeast Asian countries, Cambodia had numerous village-based rice mills operating on diesel gensets. Due to the availability of sufficient feedstock and expensive diesel fuel, these mills were an attractive market for rice husk gasifiers. A local NGO called SME Cambodia was established to introduce renewable energy, specifically targeting rice mills. A team from the NGO attended training courses at IISc in Bangalore in 2002, and also in Sri Lanka and China.

In 2005, SME Cambodia initiated a 7 kW demonstration gasifier for rural electrification based on Ankur technology. Ankur provided the design specifications for local manufacture of the main components, and SME introduced some modifications for smoother operation. The American company E&Co became part-owner of a new company SME Renewables (SME-RE) in 2005. SME-RE continued the production of gasifiers for the private sector (mainly rice mills) and secured exclusive rights from Ankur for supplying gasifiers in Cambodia, Laos and Vietnam.

The first rice 200 kW husk gasifier was supplied in August 2006 and achieved 3,000 operating hours in its first year (personal communication, Erik Middelink of SME-RE, November 2007). A second installation was installed at a brick factory and over the following decade almost 45 projects were completed in Cambodia. The business model was based on a 5-year loan to the customer to finance the plant. The money was paid back through diesel savings. The business model was initially a success, with the realisation of 30-40 units, but after a few years, E&Co withdrew, reportedly due to financial problems and corruption. The owner of SME-RE was an American who is believed to have taken a decision to close the business and then left Cambodia in 2014.

At that time there was some interest in Laos, but the market was limited because of the high potential there for hydro power. Interest in Vietnam was also limited because grid electrification expanded rapidly (over 90% connectivity) and electricity was relatively cheap. In Vietnam, many public buses operated on producer gas made from charcoal until the 1990s, so there was a huge market for charcoal. Charcoal stations (similar to petrol stations) could be found along the coastal roads.

Lessons learned: local manufacture based on imported technology is one way to reduce capital costs and develop a local market for biomass gasifiers. However, such development should preferably be embedded through the involvement of extensive technical support from a local knowledge centre and local technical, engineering and manufacturing capacity.

Rice husk was once seen as waste but is now a commodity in certain regions like western Cambodia. It is even exported to Thailand. Such trends had a huge impact on the pricing of the feedstock.

Case study 2: Majalengka and Balong, Indonesia

In the early 1980s, a large number of parallel activities focusing on wood-gas power plants took place in Indonesia. Some of the projects were based on imported equipment, while others relied on foreign designs manufactured under licence, and others still were based on local design and manufacturing, mostly with foreign technical support.

Two gasifiers were manufactured locally, building on the research of two Indonesian PhD students studying at Dutch Universities on the design of rice husk and rubber wood gasifiers. The Department of Chemical Engineering and the Centre for Research on Energy at the Institute of Technology in Bandung (ITB) were involved in developing gasification R&D and demonstration projects. Two gasifiers were realized: a rubber wood gasifier in Balong and a rice husk gasifier in Majalengka. Both were part of the UNDP/World Bank Biomass Gasification Monitoring Programme (BGMP) (H Stassen, 1995). They generated considerable experimental data.

At Balong there is a rubber plantation and a small housing area for the workers. A 20 kW_e downdraft gasifier was designed and constructed by ITB. The gasifier was close-coupled to a dual-fuel diesel engine. The second installation was a 15 kW_e open-core rice husk gasifier in Majalengka, also of local ITB design and close-coupled to a dual-fuel diesel engine.

Figure 22. Gasifiers at Balong and Majalengka, Indonesia

Source: (Knoef, 2005)

Using the knowledge, training and design capacity of ITB, both plants were modified and improved until they operated satisfactorily. Monitoring results showed that the Balong gasifier operated quite reliably for more than 11,000 hours with recorded technical availability of 85% in 1988. The locally developed small-scale rice-husk gasifiers never reached that stage, but the villagers were very keen to keep the installation in operation.

Lessons learned: The extensive technical support provided by ITB during the initial years of the project was a major success factor for both plants. The villagers partly invested in both installations (for electricity lines) and this created motivated operators who were willing to operate the gasifiers and were convinced of their ability to do so.

Case study 3: Charcoal gasifiers in Brazil and the Philippines

Charcoal gasifiers dominated the re-introduction of small gasifiers for engine operation in a number of developing countries in the 1980s, particularly in Brazil and the Philippines. Thermal gasification of biomass was already widely used in both countries and it was felt that charcoal-based technology would cause fewer operational difficulties than gasifiers using wood or agricultural residues. Around 500 charcoal gasifiers were installed in the Philippines and around 1,000 in Brazil. Within ten years, however, 90% were abandoned due to inadequate training and high service and operational costs.

Five charcoal gasifiers were part of the previously mentioned UNDP/World Bank Biomass Gasifier Monitoring Program. A novel gasifier design was developed at the Asian Institute of Technology in Bangkok, Thailand, based on ferro-cement technology. It was a relatively simple design that could be constructed for farmers using simple tools. Despite several marketing efforts, however, this development never reached commercialization stage, mainly due to high feedstock costs.

Lessons learned: Charcoal gasification can be interesting at a very small-scale if charcoal is available at reasonable cost or if no alternative power production is possible. Charcoal gasifiers are relatively cheap, simple and clean to operate, compared to gasifiers for wood and agricultural wastes.

Case study 4: Imported gasification projects

Most gasification projects in developing countries are the result of donations through various development programmes. Several of them use imported technology, causing a variety of problems.

A typical example was a 5-year cooperation programme between the Ministries of Forestry from Indonesia and Italy. The program consisted of three phases: (1) introduction of eight Italian made gasifiers to Indonesia; (2) technology transfer to Indonesian companies for local manufacture; and (3) large-scale implementation with Italian support. During the first stage, gasifiers were installed at different locations using Italian Otto gas engines. Within a couple of months, it became clear that this initiative was a failure because there were no spare parts for these engines in Indonesia, and the Italian technology supplier lacked the motivation to invest in building up a local supply chain.

Figure 23. Three Italian made 'SES' gasifiers at a sawmill, Indonesia

Source: (Knoef, 2012)

Lessons learned: In projects using imported technology, initial technical problems often result in prolonged equipment shutdown, while waiting for foreign technicians, equipment or spare parts to arrive. Those long periods of inactivity have a demotivating effect on owners and operators. This problem was enhanced in the Indonesian case because many imported gasifiers were installed in situations lacking commercial logic. For example, a 30 kW_e plant was installed in a sawmill at Sembubuk generating 3 MW_e from diesel gensets, offering negligible potential for fuel savings.

Case study 6: Experience in other selected non-SSA countries

Figure 24. Mass production of GEMCOR gasifiers in the Philippines

Source: (Knoef, 2005)

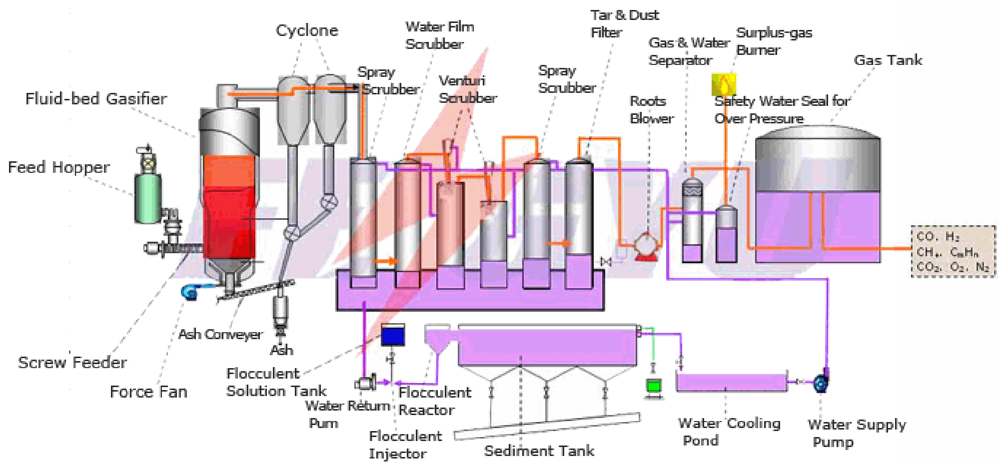
The Philippines. Serious efforts at promoting the use of gasifier technology in the Philippines were initiated in 1981. At that time, gasifiers were seen as a solution to the problem of high fuel costs for small pump irrigation systems and rural industries. During the height of the implementation of the Gasifier Program, the now defunct Gasifier and Equipment Manufacturing Corporation (GEMCOR) was a major player that concentrated its effort on stationary gasifiers for both shaft-power and direct-heat applications. By June 1983, 1,661 gasifiers had been manufactured, 331 of which were installed at various locations across the country. Commercialization of gasifiers did not succeed because of constraints limiting their use. First, most gasifiers used for shaft-power operate best under steady-state conditions, particularly when wood is used as fuel. Gasifier operation becomes complex in applications where the engine runs with intermittent or highly variable loads. Second, gasifier technology requires a reasonable level of technical competence to operate and people in rural areas found it too complex. With the closure of GEMCOR, the manufacture of gasifiers on a commercial scale came to an end.

Brazil. The use of producer gas for electricity generation is not yet established in Brazil, but use for thermal applications is quite widespread. The Brazilian National Centre for Biomass (CENBIO) at the University of São Paulo had a joint-research project with the Biomass Users Network of Brazil, the Sao Paulo Institute for Technological Research and the University of Amazonas. The project was based on cooperation between Brazil and India. Two gasifiers were imported from IISc, Bangalore. Both were tested for long-term operation and were to be installed in the field after personnel training and stable operation. Two charcoal gasifiers, one for irrigation and one for electricity production, were also introduced under the UNDP/WB Biomass Monitoring Program. The country has the necessary biomass and human resources to develop and deploy gasifier systems, but the market is still under development.

Thailand. Gasifiers in Thailand are mostly imported from manufacturers in other Asian countries, such as India and China. A study identified 26 gasification plants in Thailand in 2010, of which seven were thermal plants and 19 were for electricity generation (Salam et al., 2010). Most of the plants for electricity generation were fixed-bed downdraft units in the range 10-400 kW_e. Rice husk and wood chip were the two main feedstocks, with maize cobs, waste plastic, charcoal and old tyre rubber also in use. Almost all of the plants for electricity generation failed after a short period of operation. The study identified high tar content as the major technical barrier. Monitoring of fuel properties and gas quality was also very poor, as none of the failed plants routinely measured the moisture content or calorific value of the fuel, or the composition or flow rate of the producer gas. There were additional non-technical barriers such as inadequate feedstock supply and high prices, as well as a lack of trained operators for imported plants.

China. Many small rice husk gasifiers of different designs and sizes (25-50 HP) were installed in China in rice mills during the 1950s to provide shaft power. In the late 1960s, the government entrusted the Ministry of Commerce to design and develop large-scale gasifiers to provide electric power to larger mills. The model 6250 M1 gasifier was developed in the early 1970s to provide around160 kW_e of power for this purpose. Such a unit was also installed at Dogofiry in Mali. Many R&D organisations are active in China and several spin-off companies have emerged. One of them is Fengyu, who design fluid bed gasifiers. Since 2010, they have installed four units in Africa. Those in Tanzania and South Africa are not functional due to closure of the host companies, while the status of a plant at a sawmill in Kenya is unknown and a unit in Egypt plant is still thought to be operational.

Figure 25. Fengyu gasifier including scrubbers and gas storage tank



Source: (Salam et al., 2010)

Indonesia. The early 1980s saw the commencement of several activities on biomass gasification in Indonesia (H Stassen, 1995). Some of these projects were based on imported technologies (including the Italian project described above), while others relied on local design and manufacture with foreign technical support, and still others on foreign designs manufactured under licence. As part of the UNDP/WB Biomass Monitoring Program, 49 gasifiers were identified, mostly R&D and demonstration projects. None could be considered truly commercial in the sense that the customer paid for the equipment. Only nine heat gasifiers could be seen as commercial units as they were not financed by donors. ITB provided most of the know-how, with technical assistance from the Netherlands. Since 2000, there has been no serious interest in gasification, mainly because the whole country is now grid-connected.

Vanuatu, Pacific region. Financed by the EC/LOME II programme, several gasifiers were installed in the Pacific region, the first being at a school in Onesua, Vanuatu (H Stassen, 1995). A 29 kW_e unit was imported from the Netherlands and fully financed, with the school responsible for operational costs. The plant was a success, with 9,000 operating hours over two years. This was due to: (1) the prolonged presence of an experienced expatriate to solve technical problems, train operators and set up O&M procedures; (2) awareness within the school management of the financial benefits that could be realised through the gasifier, so they could motivate the operators; and (3) Institutional support via the EU programme enabling the project to keep in contact with the technology supplier overseas, arrange spare parts in time and discuss possible modifications based on site-specific problems (like salty feedstock). This gasifier is one of very few equipped with a minimum load device – if the load dropped below 15 kW_e, a parasitic load for water heating was brought online. This allowed the system to be operated with high loading for maximum efficiency and gas quality.

Mali. The best-known rice husk gasification system based on Chinese Technology was installed in Mali in 1967, through a joint cooperation between Mali, German, and China (H Stassen, 1995). This resulted in a 160 kW_e rice husk gasifier at a large rice mill near the village of Dogofiry. The plant was part of the BGMP and had operated for more than 55,000 hours by 1986. The plant owners were very satisfied as they only calculated the operational costs and the direct savings in diesel. But the BGMP monitoring reports concluded that despite its apparent success, there were significant drawbacks to replication. For example, the gas cleaning system consisting of a number of scrubbers was quite efficient for dust removal, but a lake of contaminated wastewater was created near the village. A second problem was the limited tar removal capacity, which required labour-intensive engine maintenance with adverse effects on economic performance. A Chinese technician had to supervise it constantly to guarantee smooth performance. This technician was the only person able to address the specific technical problems (in particular with gas cleaning). Replicability and long-term sustainability were therefore not achieved. This ultimately led to closing down of the plant after about 30 years of operation.

Seychelles and Burundi. As part of the BGMP, one gasifier was monitored in Seychelles and one in Burundi (H Stassen, 1995). In the early 1980s, three additional gasifiers were imported to the Seychelles through bilateral programs with Switzerland, Sweden and France, to be operated on a blend of coconut husk and shells. Testing revealed that none of the gasifiers could work reliably on this feedstock, however. But the French gasifier was tested successfully using wood blocks, showing the sensitivity of gasifiers to feedstock properties. Around the same, time a 36 kW_e imported wood gasifier was installed at a tea factory in Burundi. It was to be fuelled with local peat, but the BGMP established that this was not possible due to high ash content. These efforts marked the end of biomass gasification efforts in those countries.

Figure 26. Dumping of gasification residues at a rice mill in Battambang, Cambodia (2014)

Source: (Nguyen & Ha-Duong, 2014)