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ELECTRICAL VALORIZATION OF BAMBOO IN AFRICA

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Technical benchmark of small-scale woody biomass-to-electricity technologies
Application to INBAR's project to valorize bamboo in Rwanda

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Introduction

Background

In June 2010, the International Network for Bamboo and Rottin (INBAR) met Rwandan leaders to develop strategies for conserving biological diversity while meeting the needs of the people and economic development. The project is a response to the local needs.

INBAR's Livelihoods and Economic Development Program is currently developing a new project for environmentally-friendly, sustainable energy in the Republic of Rwanda.

This project will be the first INBAR project including energy access. Another project that includes electricity is being developed in India but remains at its theoretical phase, in addition it is of different size and scope comparing to the Rwandan project.

As a consulting company specialized in the energy field and access to energy in developing countries, ENEA Consulting has been asked technical (and more generally, project management) support to assess what would be the best available technologies to fit with the project's objectives and local context.

This work has been done on a voluntary pro-bono basis, part of ENEA Consulting's dedication of 20% of its consultants' time to development organizations working to improve energy access and increase climate change issues' awareness in developing countries.

General description of the project

The project has the objective to plant a minimum of 50 hectares of bamboo which will have 3 main objectives:

- Supply electricity to a minimum of 100 households
- Create a cooperative to train local communities to make bamboo products/furniture
- Introduce bamboo charcoal into local markets as a substitute to wood charcoal

Objectives of the study

The objectives of ENEA Consulting study are to help INBAR to evaluate the technical feasibility of the project, through the following steps:

1. Technical benchmark of the various biomass (and more specifically bamboo)-to-electricity technologies: description of each technology's principle, advantages and drawbacks, flexibility to a change in biomass, scale-up feasibility, etc.
2. Comparison of environmental impacts of the technologies.
3. Preliminary economic assessment of a project realized with the most relevant technology(ies), based on available data.

Executive Summary

There are a lot of ways to produce energy from biomass. The appropriate technology for a given project depends on various parameters, such as the expected type of energy and application, nature of the biomass, size, economical and environmental constraints.

Three main valorization paths are suitable to convert the energy contained in woody biomass: **combustion**, **pyrolysis** and **gasification**. Each one of them converts biomass energy to distinct intermediate energy vectors (steam, syngas, etc.), implying distinct downstream equipments (typically engines) to ensure electricity generation from these vectors.

This report describes in details each one of these processes' principles, advantages and drawbacks, available technologies and equipments, including all types of associated engines that can be used to generate electricity for local populations.

In particular, all relevant data about efficiency, maturity and liability, operational controls and performances, feedstock requirements, by-products valorization and environmental impacts are, among other things, described and compared.

Combustion, which consists in the complete combustion of biomass in an excess of air, typically takes place in combustion chamber followed by a heat exchanger where the hot flue gas stream transfers its heat to another fluid. This secondary heat vector, which is typically water (within a boiler) but can also be air or organic fluids such as thermal oils, conditions the choice of the downstream power engine, respectively steam engines and turbines, Stirling engines or ORC engines.

Technical benchmark shows that the system that is best technically and economically suited to very small-scale decentralized rural areas and more precisely to the INBAR project, would be the association of a fire tube boiler and a steam engine. Equipments are more complex to operate (temperature and air supply controls are particularly critical) and less efficient compared to gasification, but they are also more mature and wide-spread. Biomass quality requirements are also lower.

However, suppliers for small-scale biomass combustion solutions are still rare and it appears that the boiler-steam engine option would not be feasible under 70 kW. Higher investment costs and operating complexity imply a need to maximize operating times and power production's stability. This option would thus be more adapted to higher and longer local needs than supplying a hundred households for three hours a day, i.e. running at least 12 hours a day with several economical activities around connected to the plant through a micro-grid.

Within **gasification**, which occurs at high temperature and with an oxygen deficiency, the primary energy contained in bamboo is transferred to another combustible fuel, this time gaseous. This syngas, a mixture of CO, H_2, CH_4 and CO_2, can then be burnt in an internal combustion gas engine to produce electricity. All matter that does not gasify ends up under the form of another reaction output, charcoal, which may be valorized further on as a secondary fuel for heat production.

Within INBAR project's context, a fixed downdraft air gasifier coupled with a spark-ignition "Otto" engine would be the most relevant technical and economical option, as well as from an environmental point of view. Integrated equipments, such as the 20 kW GEK power pallet, seem to be a promising option that would need to be further investigated (a pilot will be tested within few months by French CIRAD).

One of the critical aspects of gasification operations is to reach a sufficient quality of syngas and low temperatures in order not to damage the engine. In that matter, particles and tars management is particularly essential. This implies dedicated equipment and their associated operating costs, as well as toxic residues handling. Wet solutions must be avoided as much as possible in order to avoid waste water treatment, but it is almost impossible to cool and clean the syngas with no water due to its unbeatable cost-efficiency ratio.

Gasification process using a steam engine is much more adapted to a small scale 20 kW flexible power production than combustion. Nevertheless, even though it has lower capital expenditures than combustion, it also has a lower lifetime and higher operating costs. In addition, it still has a poor reliability and necessitates very dedicated and skilled operators. An important number of projects that have been launched in the past have been shutdown. This option is obviously not without risks and opting for this valorization path would necessitate appropriate support from experienced entities, as well as sufficient subventions to cover financial risks.

Table below summarizes elements to compare both valorization paths.

	COMBUSTION PATH	GASIFICATION PATH
Efficiency	Lower efficiencies (10-15%)	Efficiencies between 20-25%
Maturity and robustness	Combustion is a proven and simple technology Steam engines are relatively robust technology	Gasification still needs to be proven in long-term operation: poor to reasonable reliability Gas engines are robust and widespread
Operability	Quite simple. Still, boilers need close monitoring and maintenance	Quite difficult: dedicated and skilled engineering support needed
Flexibility: *to change in biomass* *to change in load*	Higher flexibility	Lower flexibility
Start-up / Shutdown	1 – 3h	0,25 - 0,5 h
Main safety issues	High-pressure steam, explosion	CO release, explosion
Main environmental impacts	Flue gas emissions	Low level of NOx emissions Tar disposal (waste water pollution)
Investment costs	Higher investment costs Around 140 k€ for 70kW	Lower investment costs Around 30 k€ for 20kW
Expected lifetime	20-25	10-15
Operating costs	Lower costs per unit of electricity	Higher costs per unit of electricity High fuel and maintenance costs

Last but not least, type of electricity supply must be adapted to needs and it must be acknowledged that wire-pulling is not the only solution. Investment costs can rise very quickly (8000 €/km), then if the power need is equivalent to only one or two 15W lamps three hours a day, building a wire to each household would probably not be the most suited solution.

Other systems can be set up, such as “electrical blocks” distributed over the village or town center. These blocks gather streetlights, free plugs or even shared electrical devices such as a fridges or radios. These little electrical centers can be associated to key social places such as schools or any other place where people are used to gathering, enhancing activities and social exchanges around these spots. This also limits the number of wires to be pulled and associated expenditures.

A battery rent activity can also be built, charging batteries in the morning with a certain amount of energy and having people paying for a one or two days renting (depending on consumption and battery capacity). Two main advantages of this system are that it requires lower capital than building a micro-grid and that it allows power generator to run on a much more stable and controlled basis. Moreover, additional job(s) related to battery rent business management may enhance local social impacts of the project on a longer term basis than a one-shot low-maintenance-micro-grid building.

Same as for the choice of technology, the type of electricity supply would thus depend on the quantity of electricity to provide as well as the types of local uses. The table below sums up potential associations between these parameters:

	COMBUSTION PATH	GASIFICATION PATH
Type of electricity need/use	▪ High load constant power production from 70 kW upward ▪ Bring light to 100 households + economical activities with constant needs ▪ Micro-grid to connect businesses and electrical blocks	▪ Flexible power production from 20 kW upward ▪ Bring light to 100 households (+ limited economical activities) ▪ Micro-grid to electrical blocks, or battery / lamps renting system

To be noted, depending on the project's priorities, **pyrolysis** stoves could be used to maximize charcoal (or bio-char) production, and still be able to gather enough syngas (which contains more energy than gasification syngas) for domestic power uses. But the main barrier to this option, would be to handle pyrolysis oils which would not be easily reusable in this rural environment.

In any case, it is necessary to have a better insight on the local context and needs before making any choice between these different options. Some examples of data that would need to be collected before going any further:

- What are the actual local individual needs for electricity ?
- What are the local economical activities ?
- What is the population concentration ? How dense / scattered ?
- Are people ready to pay for electricity ? How much ?
- Are there areas with people already using electricity (diesel generators…) ? What is the price for a kWh of electricity ?
- What are the fuels currently used for ? (Ex: cooking ?) Is there a market for charcoal ?

To finish with, surface assessment showed that 1 or 2 ha of bamboo a year would be sufficient to supply a power plant of this range. Considering that all bamboo culms are not harvested at the same time but only the oldest 20%, 5 to 10 ha would be needed, depending on the technology type and plant exact size. From a general point of view, the power plant should be integrated as much as possible within the bamboo platform, and any potential synergy between electricity production and other bamboo activities (transport and storage logistics, power supply to a furniture manufacture, etc.) must be promoted.

1 Energy production from biomass: paths and stakes

1.1 Valorization paths from biomass to energy

There are a lot of ways to produce energy from biomass, such as illustrated in Figure 1. They are gathered in two general technological families: thermo-chemical processes and physico-chemical processes.

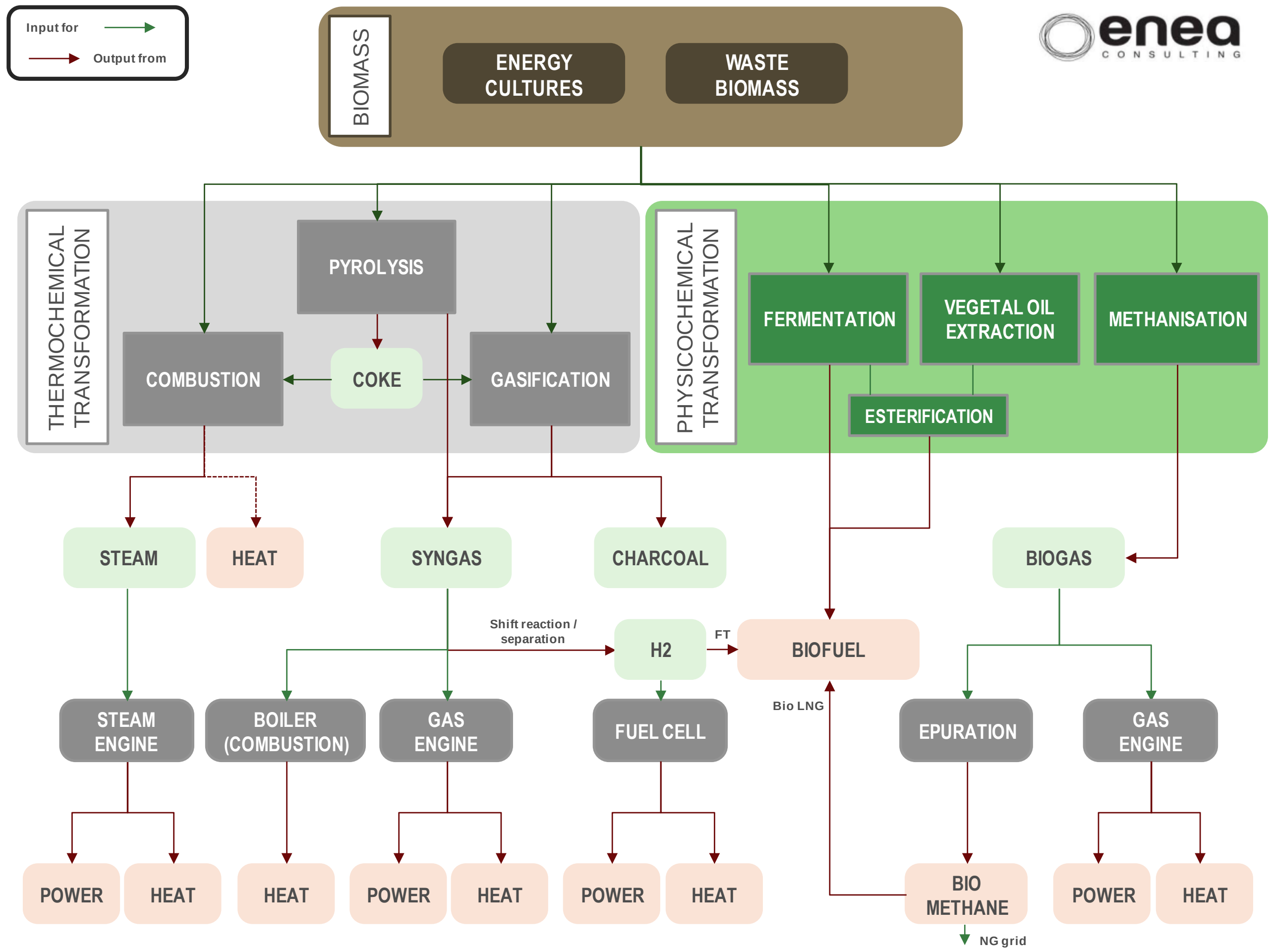

Figure 1 - Different valorization paths for energy generation from biomass, Source: ENEA Consulting

The choice between the different types of valorization technologies depends on both:

- The nature of biomass
- The type of final energy form and application expected: heat and/or electricity, biofuels, chemical products and utilities…

Mainly, fermentable ("biodegradable") and wet biomass will preferentially go through a physico-chemical path while woody and dry biomass will have to be thermo-chemically converted to useful energy.

As bamboo clearly belongs to the second biomass category, we will focus on thermo-chemical solutions, which are, respectively:

- Combustion
- Pyrolysis
- Gasification

1.2 Valorization paths from dry woody biomass to electricity

In addition to this first selection criteria, and as the project objective is to produce electricity, attention will be paid exclusively on the electricity generation paths and associated equipments.

- Following combustion, this can be ensured using external-combustion engines, such as steam engines, sterling engines or Organic Rankine Cycle (ORC) engines.
- Following pyrolysis and gasification, the resulting synthesis gas ("syngas") can be cooled and cleaned prior to direct generation of electricity via internal-combustion gas engines.

Technically, syngas could also be combusted to produce steam from which electricity could be generated within an integrated process, as for instance it is sometimes implemented in the solid waste treatment industry, which has to deal with high variation in feedstock quality and higher regulatory constraints regarding emissions. In INBAR's particular case, the quality and continuous supply of biomass can be assured. However, gasifying bamboo to produce syngas for steam production and finally power generation would be much less efficient and have very few interests compared to directly going through the combustion path. This solution will thus not be considered here.

For power generation at an industrial scale, gas and steam engines (turbines) can be coupled after the gasification process in order to enhance efficiency: it's called "Integrated Gasification Combined Cycle (IGCC)". In this case, syngas coming out of the gasifier is combusted in a gas turbine to directly generate electricity, and the hot exhaust gases from the turbine are used to generate steam in a boiler which is then used to generate more electricity via a steam turbine. Because only large-scale facilities are concerned by this combination, it will not be part of this study's scope either.

At last, electricity (and thermal energy) production from syngas can also be obtained using a fuel cell. But even if it may represent a promising option for the future, the fuel cell path will not be included in this study's scope due to high technological and economical requirements, here out of scope.

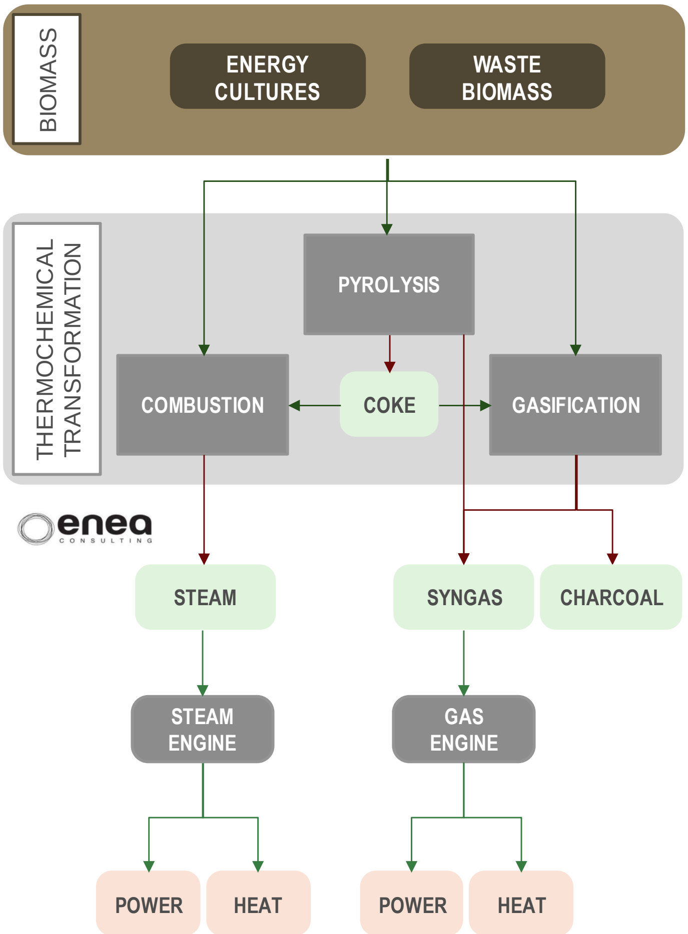

Figure 2 - Valorization paths from solid woody biomass to electricity, Source: ENEA Consulting

Finally, the technological paths that will be further investigated to answer INBAR's needs can be summed up as represented in Figure 2.

The first and main variable between combustion, pyrolysis and gasification is the relative proportion (stoichiometry) between oxygen and fuel (here biomass) needed for the well function of each process, as shown in Figure 3.

The conversion of hydrocarbons to carbon dioxide and water requires a specific molar quantity of oxygen (stoichiometric amount) to complete the theoretical reactions.

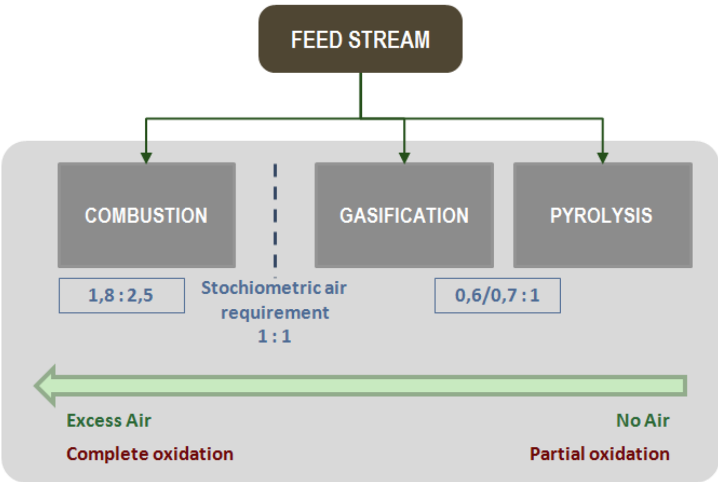

Figure 3 - Comparison of technologies in terms of need for oxidant, Source: ENEA Consulting, adapted from Juniper

Most combustion reactions require excess air (more than the stoichiometric quantity) to compensate for inherent inefficiencies in the process. On the contrary, pyrolysis and gasification involve only partial oxidation of the fuel, with less air than for stoichiometric conditions.

However, as we will see in this report, frontiers between these three processes are much thinner than one could think at first sight. Actually, all of them generally occur at various degrees and times during a thermochemical conversion of biomass into energy. Thus, what we call “Combustion process” or “Gasification process” typically describes the main reaction taking place within a given equipment.

Following sections of this report (2-4) will describe in detail each one of these processes, their principles, advantages and drawbacks, as well as associated engines that can be used to generate electricity to local populations. When available, data related to environmental impacts will also be described.

Main relevant paths will then be compared with each other, first from a technical and operational point of view (section 5), then trough a preliminary economical assessment.

To finish with, section 6 will raise the issue of energy use and the way electricity can be brought to people, underlining the fact that building a micro-grid may not be the only option and that other business models can be imagined, depending on electricity needs and local population’s organization.

2 Combustion

2.1 Technical aspects

2.1.1 General principle

Technical principle of combustion is very simple. It consists in burning any fuel composed of carbon and hydrogen atoms, under controlled conditions.

Generally, the oxygen needed for the reaction comes from the air composition. Complete combustion of biomass implies the four following steps: drying, pyrolysis, gasification and final combustion.

Pyrolysis and gasification steps will be described in other sections of this report as specific paths for energy production from biomass. In this section, the four steps that lead to complete combustion will be assimilated to the term “combustion”.

The reaction of biomass combustion can be summarized in the following reaction.

$$CH_yO_x + \left(1+\frac{y-2x}{4}\right)(O_2 + 3{,}76N_2) \rightarrow CO_2 + \frac{y}{2}H_2O + 3{,}76\left(1+\frac{y-2x}{4}\right)N_2 + \boldsymbol{Heat}$$

Equation 1 – Overall reaction of biomass combustion

The primary chemical energy contained in the fuel is irreversibly converted to heat. The fuel capacity for heat production is given by the lower heating value (LHV) which is the amount of heat produced by the combustion per unit of fuel, when steam contained in the flue gas is not condensed.

Several LHV are given in the table hereafter for comparison bewteen bamboo and other solid fuels regarding their heat production capacity.

Fuel	Low Heating Value (MJ/kg)
Bamboo – Yushannia alpina	12,97 – 15,96 (dry basis)
Bamboo – Oxytenanthera abyssinica	11,68 – 15,48 (dry basis)
Broad leaved tree (average)	18,24 (dry basis)
Resinous tree (average)	19,19 (dry basis)
Coal	15-27

Table 1 – Low heating value of several solid fuels, Source: ENEA Consulting

It must be kept in mind that bamboo will generate less energy than an equivalent weight of wood.

2.1.2 Water content and drying step

Specific attention should be given to the water content of the biomass fuel, as this parameter strongly impacts the lower heating value of the fuel.

Indeed, prior to the combustion itself, the fuel needs to go through a drying step which consists in the vaporization of the water contained in the biomass sample. This reaction requires a significant amount of energy. The more the biomass contains water, the less its combustion will produce heat , the lower the LVH will be.

Lower heating value of a wet wood can be calculated depending on its water content and its low heating value on a dry basis with the following equation.

$$LHV_{wb} = LHV_{db} \times \frac{100 - H}{100 - 6H}$$

Equation 2 – Low heating value conversion between wet basis and dry basis

With :

LHV_{wb} : the low heating value of wood on a wet basis
LHV_{db} : the low heating value of wood on a dry basis
H (%) : the water content of wood on a wet basis in massic percentage

Experience shows that if the biomass sample contains more than 60% of water, its combustion is very difficult or even unfeasible. In those cases, it could be recommended to partialy dry the ressource through other means such as an outside free storage in dry areas or by heating it with a distinct available heat source, for instance the hot flue gases from combustion.

2.1.3 Furnaces and boilers

In small scale power production applications, combustion takes place in a combustion chamber, also called furnace, followed by a heat exchanger where the hot flue gas stream transfers its heat to another fluid.

This fluid, typically water or air, can be used as a working fluid for power production through an engine or turbine, or as a heat vehicle.

Generally when air is being heated due to combustion, the equipment where the reaction is taking place is called a furnace or a stove. Figure 4 represents a wood pellets furnace with an automatic feed system. The air needed for combustion is naturally drawn into the combustion chamber by convection and the hot air exhausts by the chimney. The working fluid (air also) is moved through the heat exchanger by a draft fan.

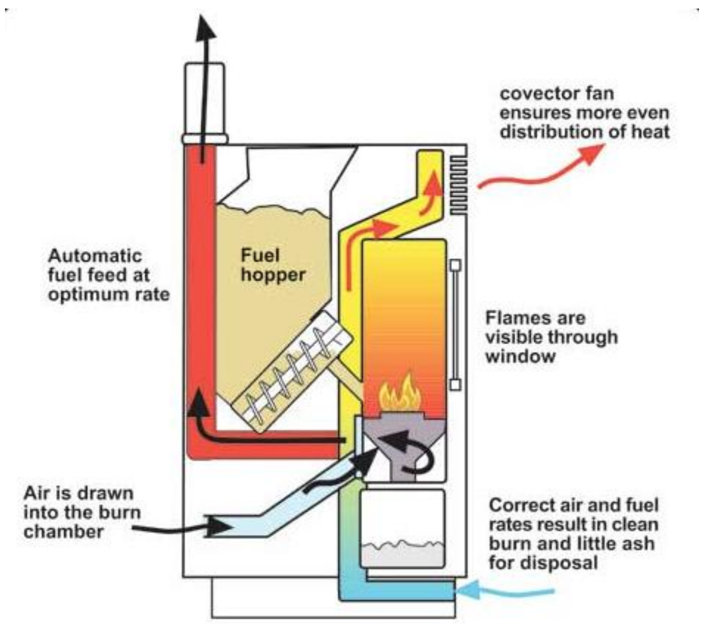

Figure 4 – Diagram of an air heating furnace, Source: Building for a future

When combustion heats water, the heat exchanger is called a boiler. There are two types of boilers:

- Fire tube boilers
- Wall tube boilers

In fire tubes boilers the flue gases pass through tubes immersed in water (cf.Figure 5), whereas in wall tube boilers, flue gases pass through wide ducts where they heat the water contained in tubes. In both cases, flue gases and water exchange heat and water evaporates.

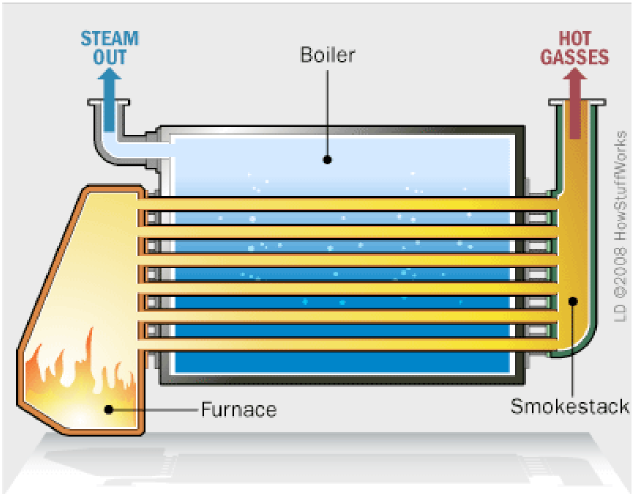

Figure 5 – Fire tube boiler, Source: Science HSW

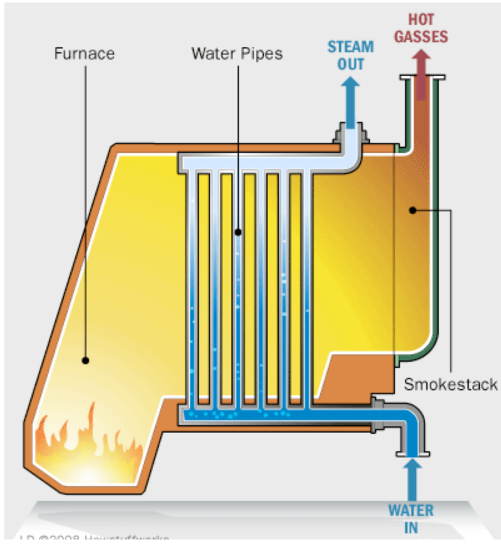

Figure 6 – Wall tube boiler, Source: Science HSW

Water tube boilers are used for large-scale steam generation at medium and high pressure (>20 bar), as they can reach high efficiency with several stages of heat exchange. On the opposite, fire tube boilers, being more compacts, are used for small scale application. Fire tube boilers operate at low pressure (below 20 bars) due to the significant volume of water that needs to be pressurized. That is why the choice of a boiler type relies on two main parameters: required steam production capacity and steam pressure.

In the specific case of INBAR's project, the need for pressurized steam for electricity generation is combined to a small steam generation capacity. Most boiler manufacturers don't currently provide equipments able to handle such requirements since electricity generation with steam is almost systematically done at large scale. Therefore, small-scale electricity production with steam would need to pay particular attention to the boiler's design, and more precisely to the steam expansion step. Given the small scale of the INBAR project, it would be recommended to use a fire tube boiler and a steam expansion device that do not require a pressure above 20 bars (cf. 2.2).

2.1.4 Combustion control

Combustion control implies a good management of the combustion which consists, in fact, in achieving the complete burn out of biomass in order to maximize energy recovery from fuel and to avoid tars production and emission of non oxidized gases such as carbon monoxide (CO) and volatile organic compounds (VOC).

To achieve a complete combustion, the biomass fuel must have a sufficient residence time in the combustion chamber with an appropriate amount of air, and a furnace ambient temperature above 850°C (The World Bank, 1999).

The pollutant gases, previously mentioned, result from an incomplete combustion. One of them that needs particular monitoring due to its severe environmental impact are the nitrogen oxides called "NOx". The most important parameters responsible for NOx production are the excess of air and a too high combustion temperature.

Therefore, the two sensitive parameters, that need to be closely monitored, are the air supply and the combustion temperature. They must be maintained at their optimum level in order to avoid an incomplete combustion as well as NOx emission.

2.1.4.1 Air supply

The combustion can be done with two types of air supply:

- Natural convection mode
- Forced convection mode

The natural convection mode consists in a free air supply where the hot flue gases going up the chimney create an aspiration effect at the furnace entrance (cf. Figure 4). This is the simplest way for air supply but it does present a risk for an incomplete combustion if the natural air convection stream is not strong enough.

The forced convection mode requires a fan placed at the entry of the furnace which pushes air inside the combustion chamber. It presents the advantage of supplying a controlled amount of air to ensure a complete combustion. But it does require a fan which increases the capital costs of the installation and consumes power.

2.1.4.2 Temperature control

The temperature inside the furnace or the boiler is influenced by the following parameters:

- Insulation: The better the insulation of the equipment is, the higher the temperature will be inside the furnace or the boiler.
- Wet Fuel: the higher the percentage of water within the biomass is, the lower the combustion temperature will be.
- Air quantity: An insufficient amount of air will result in an incomplete combustion, and an excessive amount of air will cool down the furnace or the boiler. Optimized combustion systems allow controlling the amount of air with high accuracy.
- Air for pre-heating: in order to increase the temperature and therefore the efficiency of the furnace or the boiler, the air used for combustion can be pre-heated by heat exchangers with the flue gases.

2.1.4.3 Biomass distribution

Another parameter that needs close attention, in order to avoid an incomplete combustion, is the biomass distribution within the combustion chamber. Indeed a homogeneous biomass distribution is necessary to facilitate the combustion which is why the fuel feeding system requires specific attention.

2.1.5 Environmental impacts

Clearly, it is the composition of the flue gases exhausting the furnace or boiler that can have a considerable impact on the environment. Those consist in carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), volatile organic compounds (VOC) and tars.

Apart from SOx, they all strongly depend on combustion control. When air supply, temperature and residence time of biomass in the furnace are well adjusted, emissions of these polluting gases are drastically reduced.

It should be noticed that a continuous and full load operation of the combustion facilitates its control and thus reduces the pollution emissions. Indeed, in the start up and shut down phases, the combustion is unstable.

As explained above, combustion control is the combination of numerous parameters. That is why it is a difficult task to estimate the pollution impact of a combustion system without operating it. Only technology providers can provide the gas emissions' levels relative to the type of equipment and the type of fuel used, through testing programs.

Biomass combustion emits another pollutant, dust particles, which can impact the local air quality if released in large amounts. The level of dust particle emissions depends mostly on the ash content of the biomass. At a scale of power production of 20 kW in developing countries rural areas, no regulation is expected to constrain dust emission. However a dust removal equipment can still be installed downstream from the boiler in order to limit particles emissions. In this case, a multicyclone would be recommended for its simplicity of operation and its mechanical robustness (cf. Figure 7). It should be noticed that with a multicyclone downstream from the boiler, a draft fan would be required to vent flue gas to the atmosphere.

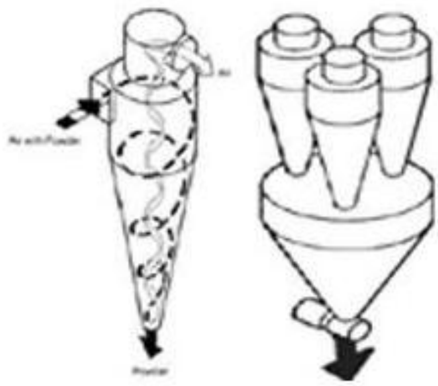

Figure 7 – Multicyclone for dust removal, Source: Clearion

As a conclusion, the environmental impacts of combustion can be drastically reduced by combustion control in the furnace and by the implementation of a multicyclone downstream from the boiler. Therefore, the emission level specified when designing the combustion system will be impacting the cost of equipments (sophisticated boiler, mutlicyclone, draft fan).

2.2 Electricity generation through external combustion

2.2.1 General principle: Rankine Cycle and Organic Rankine Cycle

Power production from external combustion is based on the use of the energy produced by combustion through the utilization of a heated working fluid in a thermodynamic cycle. It can be opposed to the concept of power combustion from internal combustion which refers to diesel engines, gasoline engines, gas engines and gas turbines.

There are numerous cycles able to produce power from external combustion, all of them implying the four steps of compression, heating, expansion and cooling. These steps allow converting heat into mechanical power by expansion through a turbine or an engine. The mechanical power produced is then converted into electricity with an alternator.

The most important issue to manage when designing a power production system is the choice of adapted technologies for both heat production and heat conversion into mechanical power. Technology suitability is highly dependent on the size of the installation and on its flexibility requirement.

On the other hand, conversion of mechanical power into electrical power is quite simple and feasible for any size and flexibility requirements. This is the role of an alternator.

The most used cycle for power production is the Rankine cycle which uses steam as working fluid and a turbine as expansion device. This cycle is not suited for applications under 1 MWe and is best suited for continuous power production applications. This is partly due to the high capital cost associated with the turbine and the high operation time needed for the economical viability of the installation. A Rankine cycle is shown in Figure 8: the fluid is pumped to high pressure going from state 1 to 2; heat is added in the boiler by the burning of fuel boiling the fluid to state 3; the vapour expands through the turbine dropping significantly in pressure and temperature to state 4; finally the vapour is condensed back to a liquid and fed back into the pump.

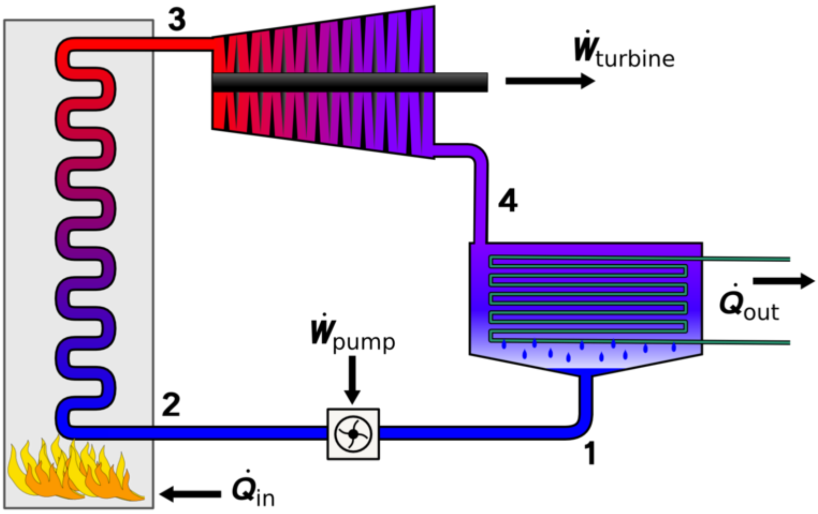

Figure 8 – Rankine cycle, Source: A. Ainsworth

The Organic Rankine Cycle (ORC), which is suited to smaller applications of power production or combined heat and power production, uses thermal oils and organic fluid instead of water. However, the ORC technology is not suitable for applications under hundreds of kWe which is far too elevated compared to the power need of the project (20 kWe). This is also due to the capital cost of the technology and its design for industrial applications.

As a result, only two technologies are suited to small scale power production from heat:

- Steam engines
- Stirling engines

Both engine types are described in the following parts.

2.2.2 Steam engines

The steam engine is the oldest device used for power production from steam.

It uses the Rankine cycle with an expansion step through pistons. When entering the cylinder, the steam pushes a piston (which produces mechanical power) and expands, lowering its pressure. During this step, the steam is cooled and when exhausting the cylinder the steam can be either released to the atmosphere or condensed, pumped and reheated in the boiler. It should be noticed that the steam released into the atmosphere induces great energy losses and therefore a fulltime boiler water feeding.

There are several kinds of steam engine that were historically invented in order to reach better efficiencies. The two main design choices that make the difference between steam engines are presented below.

2.2.2.1 Simple expansion versus multiple expansion

In a simple expansion device, a charge of steam works only once, in a cylinder, whereas in a multiple expansion device the steam is used in several following cylinders. The aim of the multiple expansion's configuration is the reduction of heat losses by optimization of heat recovery in several steps. Figure 9 shows a multiple expansion steam engine with three cylinders.

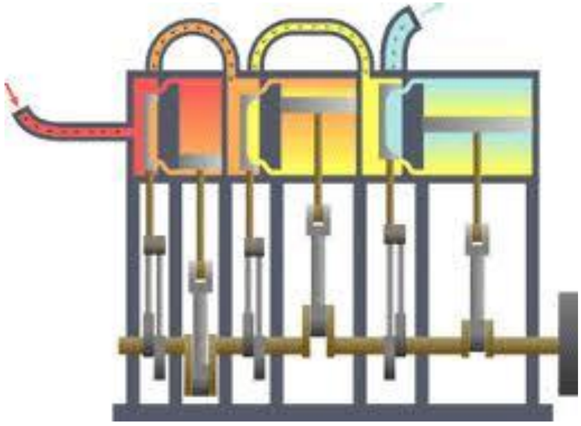

Figure 9 – Multiple expansion steam engines' principle, Source: Emoscopes

Here, the hot steam (red) enters the first cylinder and undergoes three expansions before leaving the third cylinder when cooled (blue).

2.2.2.2 Simple acting versus double acting

A simple acting steam engine allows the pistons to go back thanks to the engine inertia whereas a double acting steam engine uses steam on both sides of the piston to move it back and forth. In Figure 10 below showing a double acting steam engine, the valve rod moves back and forth to let high pressure steam go alternatively in the right and the left part of the cylinder.

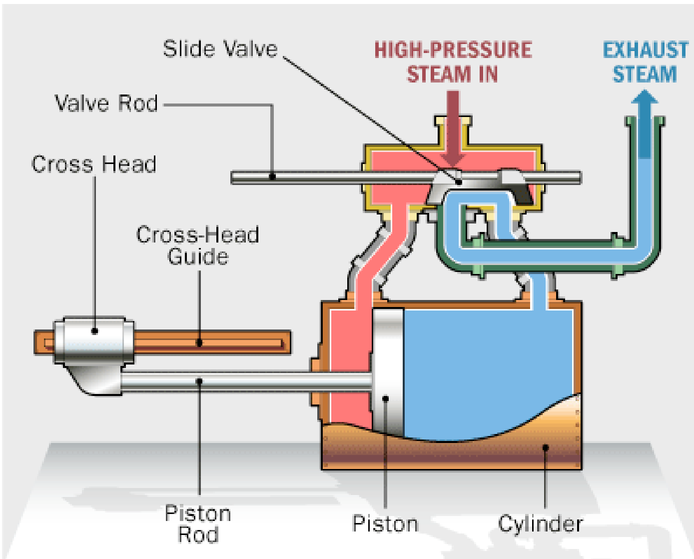

Figure 10 – Double acting steam engine piston, Source: Science HSW

2.2.2.3 Process

The use of a steam engine at small scale requires the production of steam from 15 to 40 bars. This allows using a fire-tube boiler with operation of the steam engine at a maximum of 20 bars. The fuel can be natural gas, biogas, fuel oil, coal or solid biomass.

In the case of solid biomass combustion for small scale and adapted to a rural application, air supply in the furnace can be either controlled by a fan or uncontrolled and subject to natural convection.

After expansion of the pressurized steam in the engine, the vapor should be cooled and condensed in order to loop in the boiler.

The following process diagram summarizes the steps of power production with biomass combustion and a steam engine, with air supply by natural convection.

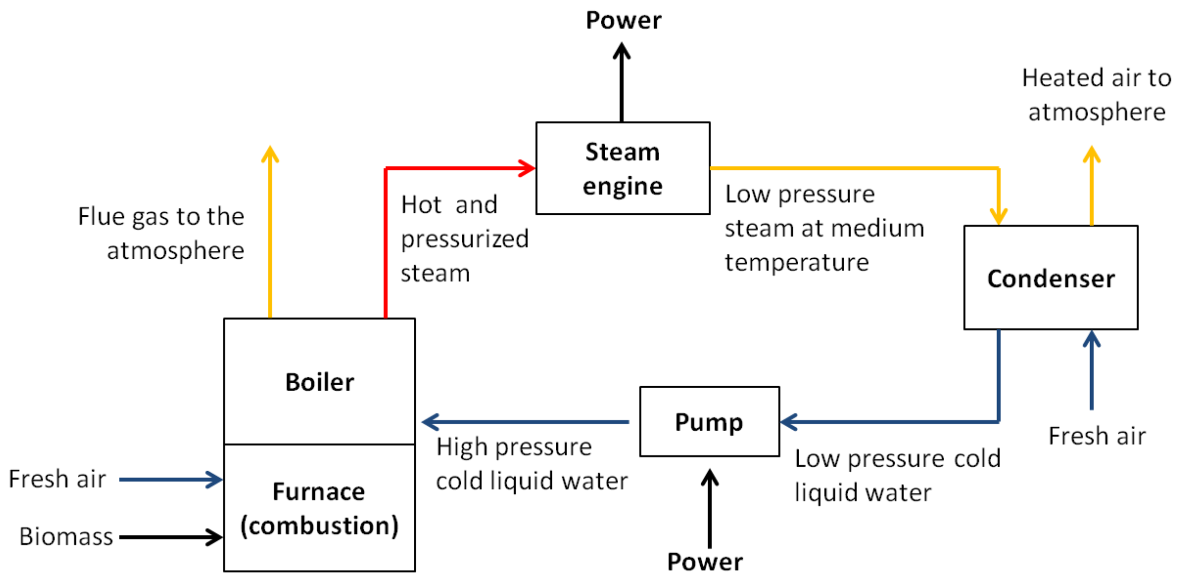

Figure 11 – Flow diagram of power production with biomass combustion and steam engine

The steam pressurization implies the presence of safety valves to release the steam to the atmosphere in case of pressurization above the design level.

A source of water should be available to feed the boiler in case of steam loss or need for temperature monitoring.

2.2.2.4 Efficiency

The steam engine efficiency is highly dependent on the inlet temperature and pressure of the steam. The more the steam is heated and pressurized, the more the engine efficiency will be elevated. Another impacting parameter is the full condensation of the expanded steam exiting the steam engine and its recycling in the boiler.

The efficiency of the boiler depends on the following points:

- Complete combustion of biomass in the furnace
- Maximization of the heat exchange within the boiler between fire tubes and water
- Minimization of heat losses thanks to sufficient insulation of the equipments

All these parameters depend mostly of the equipment's quality that will be supplied by the selected manufacturer.

The overall electrical efficiency of the process is the amount of electricity usable compared to the energy contained in the biomass injected (LHV). For small scale applications, the overall electrical efficiency can vary from 10 to 15% (SPGS & Unique, 2006).

2.2.2.5 Maturity and technical constraints

The power production with a steam engine presents the interest of being a widely tested and reliable technology. Both steam production and steam engine rely on robust equipments with low maintenance needs.

However, the steam production requires significant monitoring with quite complex procedures and equipments. One illustrating example of the boiler monitoring difficulty is the management of the boiler overheating possibility. Actually, the boiler is designed to deliver a specific amount of steam with defined levels of pressure and temperature. Theses parameters are defined on the basis of a fixed power input with biomass combustion. But when the boiler is operating, the heating input due to combustion is unstable and the water level in the boiler needs to be adjusted. If the water level is low, the steam will reach an excessive temperature that can damage the equipment. In order to balance the water level and lower the temperature, water can be added into the boiler. But this operation requires preheating of the water to avoid the introduction of cold water into a very hot environment which would create a blowup.

In addition to close monitoring, boilers require a significant level of water purity in order to avoid tube damage by corrosion and fouling. Depending on the composition of local water, the following steps of purification could be required (The World Bank, 1999).

- Particle filtration
- Dissolved gas removal
- Ion removal
- Organic compound removal

Finally, power production with steam implies equipments of significant weight and size, requiring heavy facilities such as concrete slabs and pits.

2.2.2.6 Economical aspects and purchasing

An investigation among NGOs and other actors for energy access in developing countries reveals that no steam engine application is currently in operation for power production for the scale range of 20 kWe. This is due to the elevated investment costs required by such technology.

The smallest power production project identified using a steam engine is led by the CIRAD (French agricultural research center for development). It concerns a pilot unit of 70 kWe which is the estimated minimum size for viability. . The steam engine will operate at 15 bars. The technology provider involved is Cogébio, a French company which started to commercialize a small biomass combined heat and power équipment in 2008. The overall cost for a 70 kWe equipment is around 2000 $/kWe.

Given the significant investment cost for the steam engine, this technology is recommended for applications where run time will be maximized.

2.2.3 Stirling engines

The Stirling engine is another external combustion engine that uses air, helium or hydrogen as working gas in a closed cycle. It is composed of a hot chamber, a cold chamber, a power piston and a displacer piston. The chambers communicate to let the gas move from one chamber to theother. The two pistons are linked one to the other and transfer the mechanical power to a crankshaft. The heat source can be either solar, waste heat recovery or any fuel combustion. The cold chamber is cooled by air, water or another refrigerant liquid.

2.2.3.1 Stirling cycle

The Stirling cycle is basically composed of four steps (cf. Figure 12).

1. The gas is in the hot cylinder. It is heated by the heating source. This increases the fluid temperature and pressure and moves the power piston.
2. The displacer piston is dragged by the power piston thus pushing the hot gas from the hot cylinder to the cold cylinder. The gas is cooled by the cold source and its pressure is lowered.
3. The displacer piston starts to compress the gas in the cold cylinder. The heat generated by the compression is absorbed by the cold source.
4. The displacer piston keeps pushing the gas which is transferred to the hot cylinder.

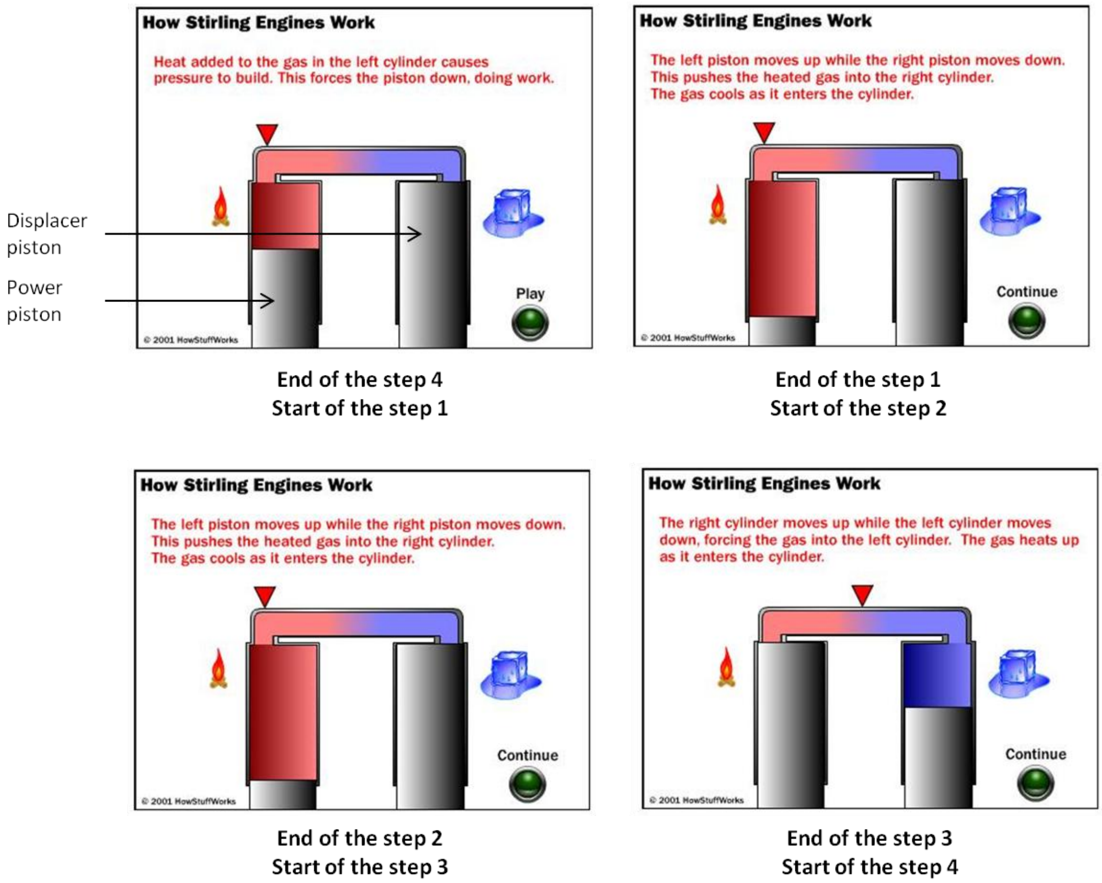

Figure 12 – The four steps of the Stirling cycle, Source: Auto HSW

Step 1 of the cycle produces mechanical power while step 3 consumes mechanical power. However, the power produced by expansion of a gas at high pressure and high temperature (step 1) is more important than the power consumed by compression of the gas at low temperature and low pressure (step 3). That is why the overall Stirling cycle produces net power.

2.2.3.2 Kinematic versus free-piston engines

Several types of Stirling engines exist, and can be separated into two families: the kinematic and the free-piston engines. A kinematic engine uses a crankshaft and complicated mechanical linkage between the power piston and the displacer piston. In a free-piston engine, the displacer piston is free to move and there is usually no crankshaft or mechanical linkage. This makes it much simpler mechanical wise but requires complex adjustment in order to control the pistons movements and optimize the energy delivery per cycle.

For decentralized applications, the most discriminating difference between the two types of engine is the stability of the delivered electric power. Indeed, a kinematic engine delivers power with regular frequency whereas free-piston engines have a tendency to generate power with irregular frequency.

Free-piston engines are preferred in on-grid applications where the grid will stabilize the operating frequency of the engine. For off-grid or mini-grid applications, the most recommended type is the kinematic engine.

2.2.3.3 Process

Stirling engine offers a wide application range regarding heating sources. They can be separated into two main configurations: hot air heating or fuel combustion. In the first configuration, combustion is operated in the area surrounding the engine's hot chamber thus exchanging heat directly (cf. Figure 13). This is suited only for liquid and gaseous fuels that can burn easily in reduced spaces.

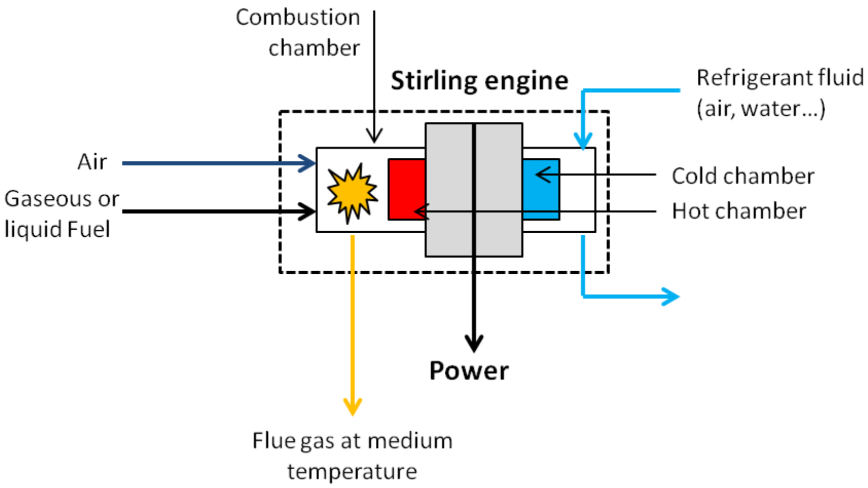

Figure 13 – Process of power production with a Stirling engine heated by gaseous or liquid combustion

In the second configuration, hot air is produced with any heating source (solar, heat recovery from industrial site, biomass or waste combustion). The hot air exchanges its heat with the engine hot chamber (cf. Figure 14). In the case of solid biomass combustion it is necessary to operate an isolated combustion and to transfer heat to the engine with hot air.

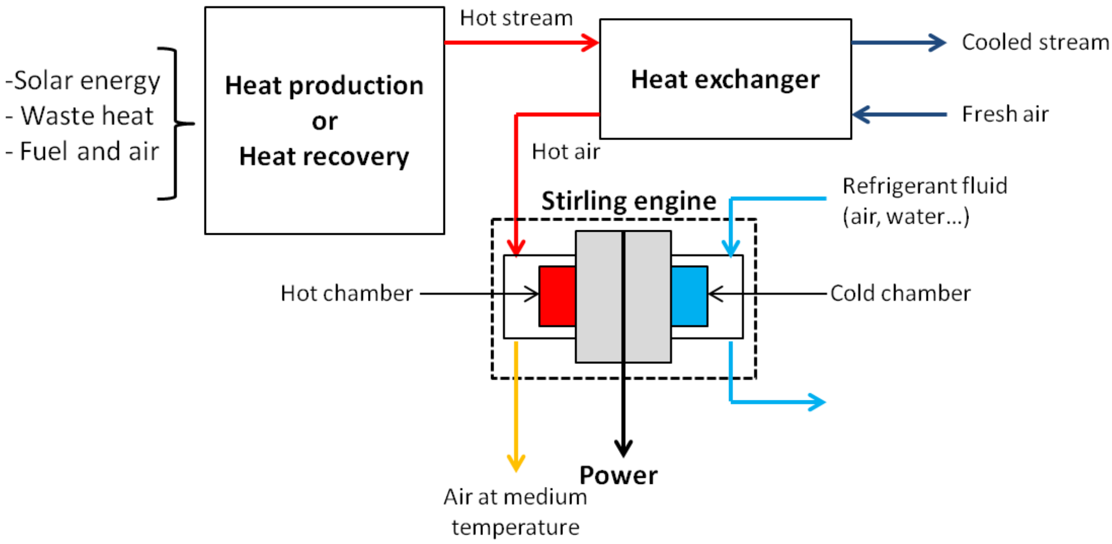

Figure 14 – Process of power production with a Stirling engine heated by hot air

2.2.3.4 Efficiency

The more the temperature difference between the hot cylinder and the cold cylinder is elevated, the more net power will be produced. This is also true for the pressure difference between the two cylinders. That is why heat exchange between the sources (heat and cold) and the cylinders is decisive for the Stirling engine's efficiency.

The most often used temperature ranges are between 650°C and 750°C for the hot cylinder and between 40 to 85°C for the cold cylinder (EPRI, 2006). Depending on the technology provider, the operating pressure can vary from 10 to 150 bars.

The nature of the working fluid also influences the thermodynamic efficiency of the engine. Air which is simple to operate is the less interesting fluid for thermodynamic efficiency whereas helium and hydrogen reach better efficiency but are more complicated to operate.

Mixing all these parameters, the overall efficiency of a stirling engine process from heat source to electricity varies from 10 to 30% (E Source Compagnies LLC, 2006)

2.2.3.5 Maturity and technical issues

Although the Stirling engine is known since the beginning of the 19th century, its development is still ongoing because of strong technical issues that reduce the engine performances and reliability. Among which:

- Mechanical and thermal losses due to friction
- Material stress and corrosion in the pressurized and hot parts (which are increased by high temperatures)
- Leakage from the pressurized parts to the outside

As a result of these constraints, few companies currently commercialize Stirling engines and many companies involved are still pursuing R&D programs.

2.2.3.6 Cost and purchasing

Given the parameters of the INBAR project in Rwanda, only one commercialized engine has been identified as viable. This engine is the only product of Stirling Biopower, a small American company. It is commercialized since the end of 2008 and the technical characteristics of the product are given in the table below. Unfortunately, no references or operational feedback are available for this product. The estimated cost of the PowerUnit™ Stirling engine is of 1200 $/kWe (E Source Compagnies LLC, 2006).

Power	43 kW (for 60Hz) / 38 kW (for 50 Hz)
Application	Off-grid
Fuel	Gaseous fuel or hot air as heat source
Efficiency of the isolated engine	27-28%

Table 2 - PowerUnit™ characteristics, Source: Stirling Biopower Company

2.2.4 Conclusion on power generation

Figure 3 summarizes the main characteristics of steam engine process and Stirling engine process for power production at small scale.

	Steam engine process	Stirling engine process
Working fluid	Pressurized steam	Air, Helium or Hydrogen
Efficiency	10 to 15%	10 to 30%
Infrastructure constraints	Heavy	Medium
Operational constraints	Combustion control, boiler monitoring, water treatment, blow up risks	Combustion control
Maintenance	Low requirement	Very low requirement
Environmental impacts	NOx, SOx, CO, VOC, tars and dust	
	Acceptable emission level are easily reached with appropriate combustion control	
Cost	2000 $/kW all equipments included	1200 to 2500 $/kW for Stirling engine only
Maturity	Reliable	Still in development (very few commercialized models with little opera-

		tional feedback)
Purchasing	Rare suppliers for small scale applications	Rare suppliers
Application to the INBAR project	Not applicable under 70kWe. Requires intense and stable power consumption (at least 12h/day).	Not currently applicable due lack of maturity and elevated investment cost.

Table 3 : Comparison of Steam and Stirling engine processes, Source: ENEA Consulting

Steam engine

The steam engine application to power production in rural areas is feasible and quite reliable. However, the inertia and the complex operability of the steam production process makes it not well suited to downscaling. As a consequence, small scale applications of power production with steam engine require an elevated investment cost. In order to ensure economic viability of the installation, it appears necessary to avoid excessive downscaling and to maximize its power delivery to consumers.

According to the CIRAD evaluation, the steam engine technology justifies a minimum scale of 70 kWe. Furthermore, we can estimate the minimum affordable operating time of the installation at 12 hours per day in order to ensure its economical viability.

These characteristics differ from the initial specifications of the INBAR project. However, the steam engine application still remains an interesting solution for bamboo valorization to electricity for off-grid villages already consuming power but currently using diffuse and unreliable technologies.

Stirling engine

The Stirling engine is suited for small scale design because its efficiency does not depend on the engine size. Current technology developers focus on the range of 1 to 100 kWe (EPRI, 2006), including using biomass combustion as a heating source. Unfortunately, power production from biomass combustion coupled to a Stirling engine has a low maturity and there is no operational feedback on its applications for decentralized rural electrification in developing countries. That is why this solution may be monitored in the future but is currently not recommended for the INBAR project or any other decentralized electrification project.

3 Pyrolysis

3.1 Technical aspects

3.1.1 General principle

Sometimes called thermolysis, pyrolysis consists in the thermal (“pyro”) degradation (“lysis”) of organic material, at a moderate temperature (350 to 600°C), in the absence of oxygen. This is the first step in the combustion or gasification of biomass.

Heating leads to a chemical decomposition of the biomass, resulting in:

- A solid phase : charcoal (or coke)
- A liquid phase : condensable pyrolysis oils and tars
- A gaseous phase : non-condensable gases (or syngas)

To schematize, pyrolysis is more or less what happens when a match is stricken, except that within a pyrolyzer, the absence (or very low presence) of oxygen globally prevents combustion to occur.

Produced charcoal, provided it is sufficiently clean (low contents of ashes, halogens, heavy metals), can then be used as a secondary fuel for thermal valorization.

Syngas, as in the gasification case, can then be burnt, either in a boiler for thermal-only valorization, or, after being cleaned, in a gas engine for power (or combined heat and power) production.

Pyrolysis oils can be further processed in “bio-refineries” to produce bio-fuels or other useful chemical products.

3.1.2 Reactions involved

Pyrolysis conversion of biomass into solid, liquid and gaseous products can be represented as the following (MM: mineral material):

$$(C, H, O, N, MM, H_2O)_{biomass} \rightarrow (C, MM)_{solid} + (CO, H_2, CH_4, CO_2, N_2)_{gas} + (C_nH_m, H_2O)_{oils,tars}$$

Equation 3 – Pyrolysis reaction, Source: ENEA Consulting

More precisely, pyrolysis comprises a quite complicated combination of physical and chemical mechanisms. Simplified, it is a mix of primary thermal degradation and secondary cracking and recombining reactions, such as illustrated in Figure 15.

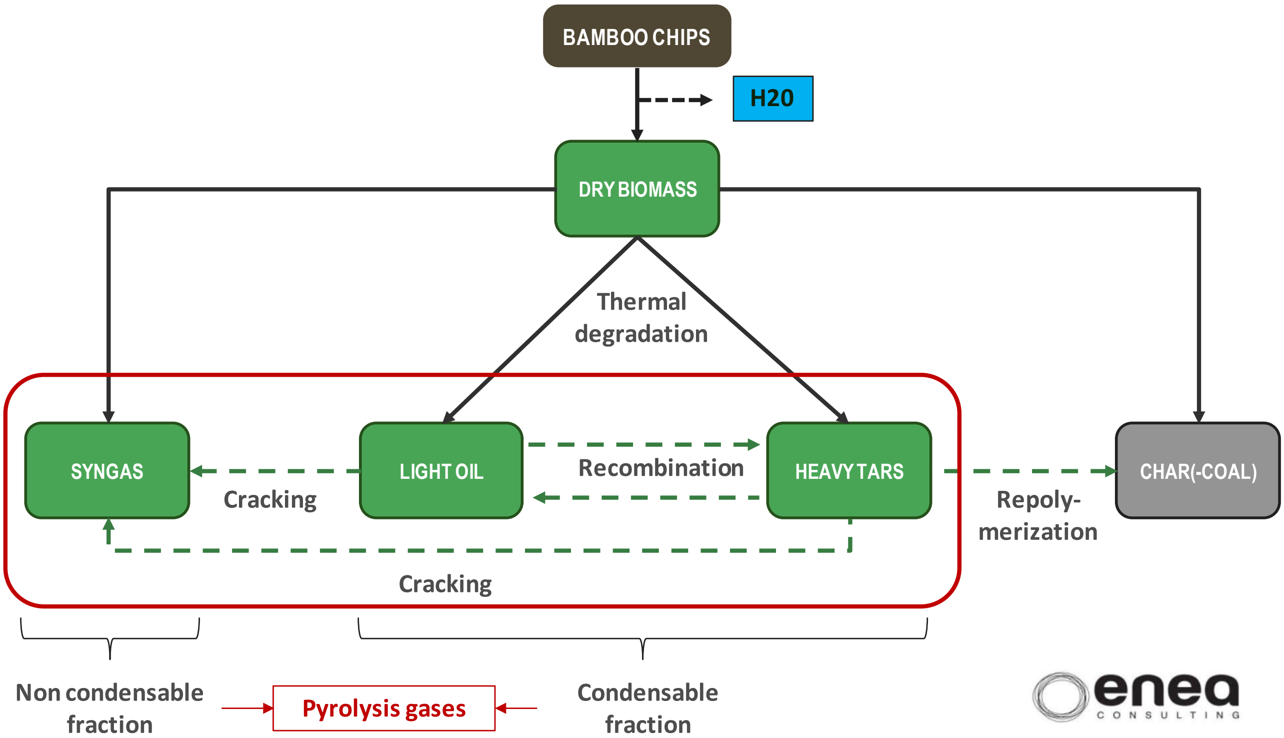

Figure 15 – Pyrolysis reactions and products, Source: ENEA Consulting, adapted from Gonec & Sunol

Contrary to combustion and gasification, which are usually exothermic reactions, pyrolysis is an endothermic reaction, which means that it requires an external input of energy (typically applied indirectly through the walls of the reactor). Hot flue gas is usually re-injected in the reactor to bring more heat and allow the plant to be autonomous once startup phase is over. In most existing installations, generally designed to optimize charcoal or oil production, produced syngas is directly recycled and burnt to provide heat to the pyrolysis reaction, which however makes power generation impossible.

3.2 Operational performances

3.2.1 Influence of temperature and residence time

Depending on the operating conditions of temperature and residence time, varying quantities of syngas, pyrolysis oils and charcoal are formed. Typically,

- High temperature (500-600°C), short residence time pyrolysis, also called thermal gasification or flash pyrolysis, will maximize the production of condensable oils (heavy aromatic, hydrocarbons)
- Low temperature (350-400°C), long residence time pyrolysis, also called carbonization, will maximize the production of coke (charcoal) and non-condensable gases (H_2, CO, CO_2)

Table 4 below illustrates typical proportions of products that can be expected from both types of pyrolysis.

For 1 ton of dry matter (DM)	Flash Pyrolysis (T = 500°C)	Carbonization (T = 350°C)
Pyrolysis gases (kg)	110	380
Pyrolysis oils (kg)	730	190
Pyrolysis coke (kg)	160	430

Table 4 - Pyrolysis type and associated products, Source: ENEA Consulting, adapted from UTC, 2010

If a pyrolysis process was selected, low-temperature pyrolysis (carbonization) would thus be much better suited to the INBAR project, both minimizing oils production and maximizing gases and coke (see 3.3, valorization of pyrolysis products).

3.2.2 Influence of feedstock size

Feedstock size will also have a considerable influence on the reaction time and the resulting gas composition, such as experimented by the Université Catholique de Lausanne, whose results are reported below in Figure 16.

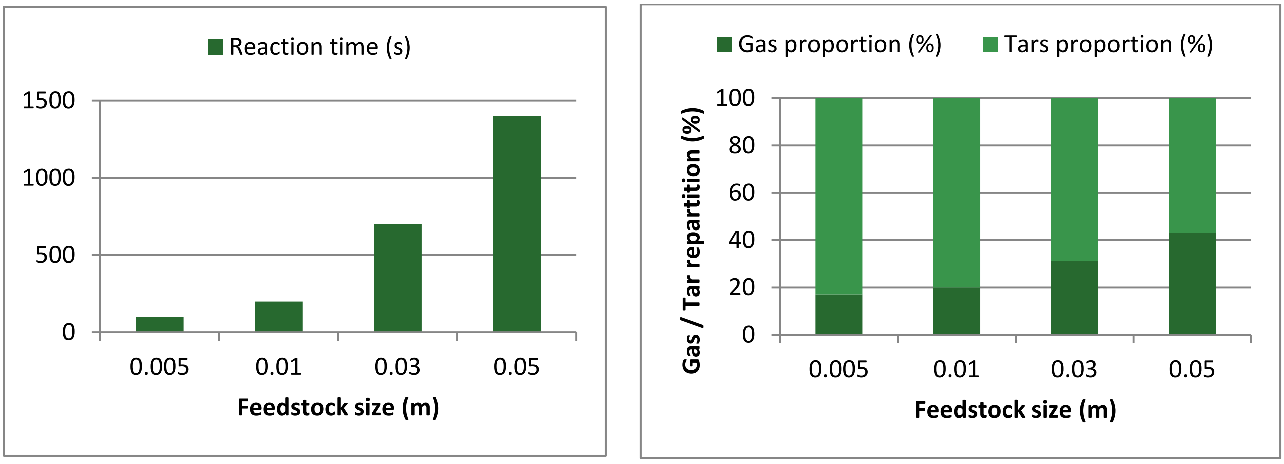

Figure 16 - Influence of feedstock size on reaction time and gas/tar proportions, Source: ENEA Consulting, adapted from UCL

As we can see:

- Small particles will allow fast pyrolysis and preferential production of tars and oils
- Bigger particles will lead to a slower pyrolysis and production of more non-condensable gases

3.3 Valorization of pyrolysis products

3.3.1 Pyrolysis syngas

Syngas produced from pyrolysis is usually a medium heating value (MHV) fuel gas, around 14-18 MJ/Nm^3 depending on feed and operating conditions. This is because it contains a high level of hydrocarbons, including uncondensed pyrolysis liquids as well as saturated and unsaturated hydrocarbons (particularly methane) resulting from the thermal degradation process. Therefore, pyrolysis syngas has a higher calorific value than gasification syngas (4-7 MJ/m^3 for air gasification, see Part 4).

3.3.2 Pyrolysis coke/charcoal

Pyrolysis charcoal or coke, apart from being disposed of (which is not an appropriate option from energetical, economical neither environmental points of view), can be reused in different ways, advantages and drawbacks of which are presented in Table 5.

Char Handling option	Advantages	Drawbacks	Relevance to INBAR project
Convert to carbon-based solid fuel	▪ Recycling and valorization of pyrolysis product ▪ Conservation of chemical energy for cooking use	▪ Need for a local market ▪ Additional handling and transport costs ▪ Additional environmental impact	

		related to transport
Gasify	▪ Conservation of chemical energy for internal use or power generation	▪ Additional capital equipment (especially if separated pyrolysis and gasification) ▪ Production of ash residues to handle/dispose
Melt into slag product	▪ Material and energy recycling ▪ Trapping of heavy metals within glass-like matrix	
Dispose	▪ Simplest solution ▪ No additional capital expenditure	▪ Lose of coke chemical energy ▪ Additional handling and transport costs ▪ Additional environmental impact related to transport

Table 5 - Comparison of main valorization paths for charcoal, Source: ENEA Consulting

With the objective to maximize direct power production, gasification would clearly be the best option, and in this context an integrated pyro-gasification would prevail on separated pyrolysis and gasification. This scenario is the object of next section.

Depending on the project's objectives, the other interesting option for reuse of pyrolysis char would be to turn it into a solid fuel for local industry or cooking applications, which often have major impacts on deforestation consuming non-renewable wood coal. To be noted that this option is also applicable to charcoal resulting from gasification process (even if it is produced in smaller quantities with gasification).

Small size and quite heterogeneity in size can make wood charcoal bits difficult to sell on markets, that is why it often goes through a standardization (briquetting) process.

Important parameter is the water content of the charcoal, which mainly depends on the way ashes (and thus charcoal) are extracted from the reactor (hydraulic or manual). In case of char-optimizing slow pyrolysis (carbonization), charcoal has low humidity (~10%) and therefore does not need to be dried.

Hereafter is an example of how standardized charcoal bits (called "briquettes") can be easily produced from pyrolysis or gasification char.

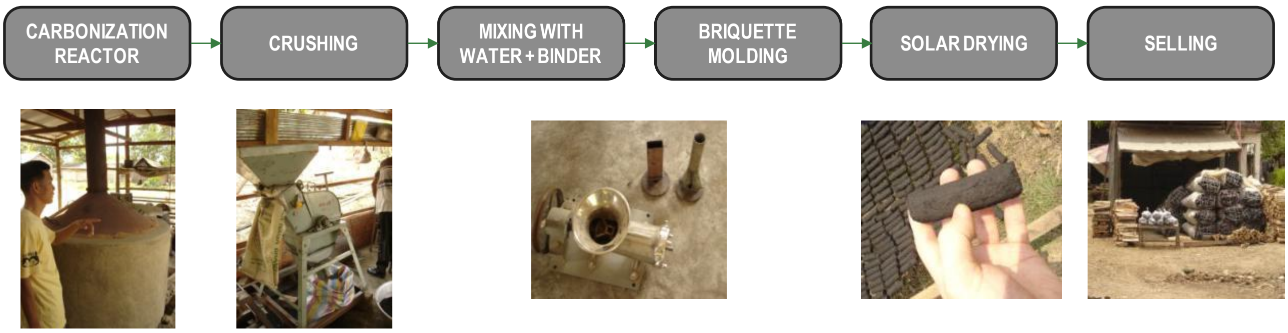

Figure 17 – Charcoal "briquettes" fabrication process, Source: ENEA Consulting, adapted from GERES, 2006

This very simple process necessitates more time and additional investments (maybe another employee). It is thus well adapted to small production rates. Manual mixing of charcoal powder with water and binder takes about 40 min for 20 kg of mix, and solar drying can take a few days, depending on the season (GERES & CSFP, 2006).

A pyrolyser designed to produce enough syngas to supply electricity to a hundred houses (considering a 10% electrical efficiency) would generate around 70 tons of bio-char briquettes a year, i.e. more than 200 kg a day (12h, 80% annual availability). A power-production equivalent gasifier would generate around 10 tons a year / 30 kg a day, while consuming half the bamboo needed for the pyrolyser.

From a socio-environmental point of view, pyrolysis or gasification charcoal is also interesting: it is not dirty, has a heating value close to conventional wood coal, has a longer combustion time, and emits few smokes. For all these reasons it is often appreciated by populations.

From an economical point of view, charcoal briquettes' selling price has to be compared to other available coals, as well as taking into account additional operating and transport costs.

3.3.3 Pyrolysis oils

Producing bio-fuels from pyrolysis oils is possible, which has the main advantage to decouple fuel production from power generation.

Power production can also be obtained from these oils but it requires several further processes and reactions to separate oils from tars and purify them (by catalytic upgrading), each step needing additional energy (and costs) and reducing global efficiency. Moreover, pyrolysis oils contain a non negligible amount of water which makes them quite unstable, causing some problems for storage and further utilization. They also have quite high particles and alkali metals levels due to char and ash carry over.

Last but not least, it is not the objective of the project to produce oils and, without any easy way to valorize them, they should be considered a constraint.

3.4 Conclusion: relevance of pyrolysis, following expected valorization

Whatever operating conditions and feedstock size, syngas production can hardly reach more than 40% of pyrolysis products. If one objective of the project is to produce bamboo charcoal ("biochar") to be sold in a bigger city around, carbonization could represent quite an interesting option and would need to be further investigated (not only technically but also economically, taking into account both charcoal selling price and additional costs of charcoal transportation to selling points). Nevertheless, there would still be around 20% of pyrolysis oils without any obvious or easy valorization path.

As INBAR's priority is to produce electricity, we therefore have not considered pyrolysis-alone processes further.

To enhance energy efficiency of the bamboo-to-electricity process, pyrolysis coke and oils can be cracked into a gasifier. Pyrolysis can then be considered as the first step of a "largo sensus" gasification process, sometimes called "pyro-gasification" for this very reason.

4 Gasification

4.1 Technical Aspects

4.1.1 General principle

Gasification is the production of a gaseous fuel from a solid fuel. It consists in a quite complex thermal and chemical conversion of organic material, at high temperature and under restricted air supply, into a producer gas (also called syngas) and ash. It includes both a pyrolysis step and a partial combustion.

The primary energy contained in the feedstock, once transferred to the producer gas, can then be converted into heat, mechanical power or electricity.

Compared to solid fuel the producer gas is easier to handle and contains lower levels of contaminants.

4.1.2 Detailed reactions involved

The gasification conversion process is made of a series of simple reactions occurring with little oxygen at very high temperatures, typically between 750°C and 1200 °C.

The figure below sums up the complex series of reactions occurring during the gasification process.

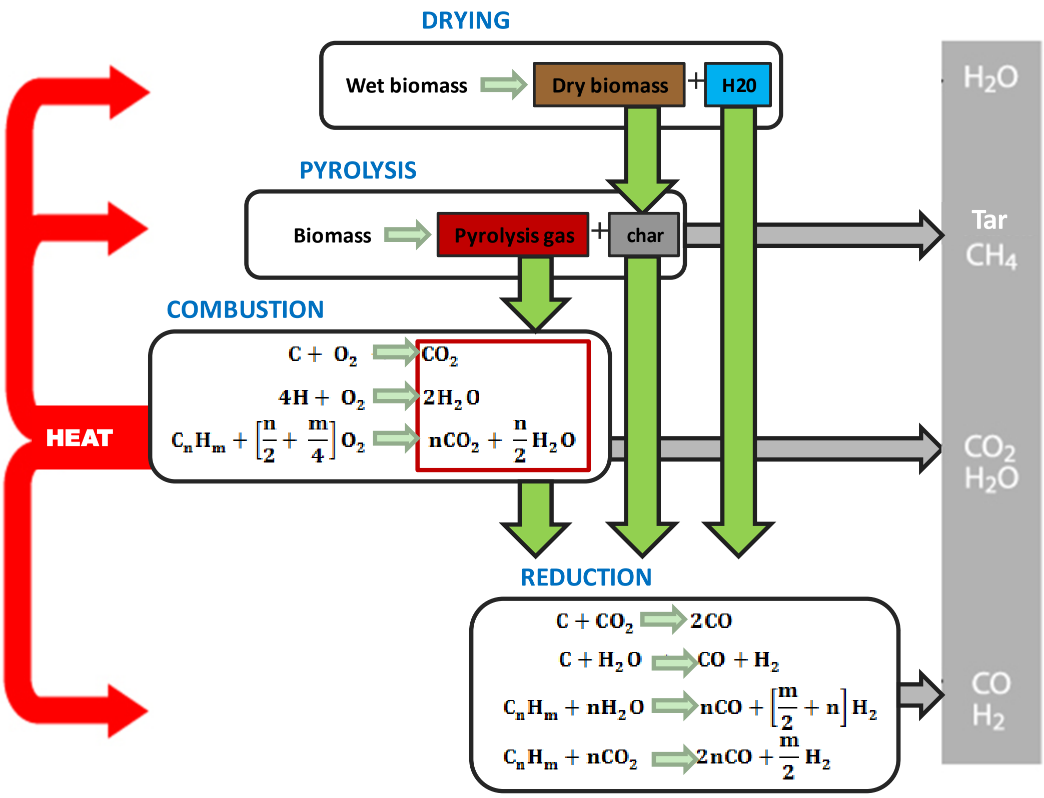

Figure 18 - Gasification process' detailed reactions, Source: ENEA Consulting, adapted from Biomass Technology Group

First, biomass is dried by the addition of heat in order to release the water from the solid materials, before being pyrolysed. In the oxidation / combustion zone, primarily vaporous pyrolysis products react with the input gasification medium (and the oxygen it contains). Gases (CO_2 and H_2O) leaking from the oxidation zone are then reduced to CO and H_2 by the charcoal (resulting from pyrolysis) in the reduction zone. These endothermic reactions use a portion of the sensitive heat of the smoke gases to store chemical energy (syngas). This also leads to the drop of the gas temperature to a level at which no further reaction between charcoal and syngas occurs. That is why there is always a layer of unreacted charcoal above the ash grate that has to be discharged with the ash (Graz University of Technology, 2007), representing around 15% of the initial fuel mass.

Products of the gasification process are syngas, charcoal and water, plus condensable as minor products.

The syngas is a mixture of carbon monoxide, hydrogen and methane (combustible gases), together with carbon dioxide, nitrogen and other incombustible gases and impurities (Balat & al, 2009).

More precisely, classical repartition between syngas components resulting from a small-scale downdraft air gasifier is represented in Figure 19.

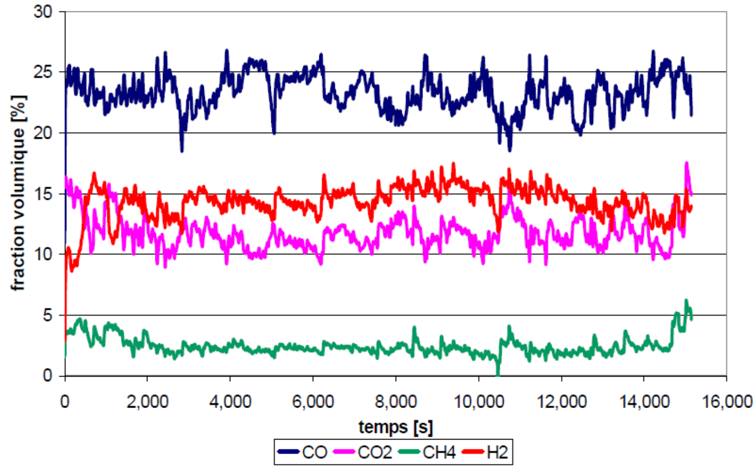

Figure 19 - Composition of a syngas from a biomass-fueled 40 kWe unit, Source: UCL/TERM

Around 40% of volume of this type of syngas is thus made of combustible gases that can be later used for power (or heat) generation.

4.1.3 Gasification technologies

A gasifier is mainly a chemical reactor where carbonaceous materials are burnt as fuel in a process of incomplete combustion due to a limited air supply, but actually there are different types of gasification technology on the market.

The type of technology applied depends on the size of the installation, the quality of the available feedstock, the quality of gas required and the environmental pollution standards. The two main types are:

- Fluidized bed gasifiers
- Fixed bed gasifiers

4.1.3.1 Fluidized bed gasifiers

Fluidization is the term applied to a process whereby a fixed bed of small solid particles (as in a coal burning furnace) is transformed into a liquid-like state, suspended and kept in motion through contact with an upward flowing gas, typically air.

The main advantage of fluidized bed gasifiers over fixed bed gasifiers is that they have higher energy conversion efficiency, enhancing contact between gas and solid and allowing a good control of the temperature and the speed of reactions.

However, they are generally not suitable for small-to-medium sized applications, typically ranging from a minimum of 200-500 kW to dozens of MW, mainly because of more complicated operations and associated costs. They will thus not be further detailed in this study.

4.1.3.2 Fixed bed gasifiers

In fixed-bed reactors, fresh biomass is fed from the top of the reactor, introduced through an opening on the reactor head and sinks slowly downwards by gravity as the conversion of fuel proceeds.

Fixed bed gasifiers are more simple and robust. They are characterized at a small scale by a high electric efficiency and their use of waste heat potential. Moreover, fixed bed gasifiers have less strict requirements in terms of biomass preparation, accepting feedstock size up to 100 mm while fluidized bed gasifiers tolerate no more than 10 mm and a moisture content under 15% (for entrained fluidized beds).
There are two main types of fixed bed gasifiers, which are characterized by the relative direction of gas stream and fuel bed movement, namely:

- "Updraft" or counter-current
- "Downdraft" or co-current

In an updraft gasifier, the gasification medium (air, oxygen, heat) and the produced syngas flow through the gasification reactor in the opposite direction to the biomass fuel bed.

Within downdraft configuration, both biomass and gasification medium migrate in the same direction thus produced gas outlet is situated near the heater side.

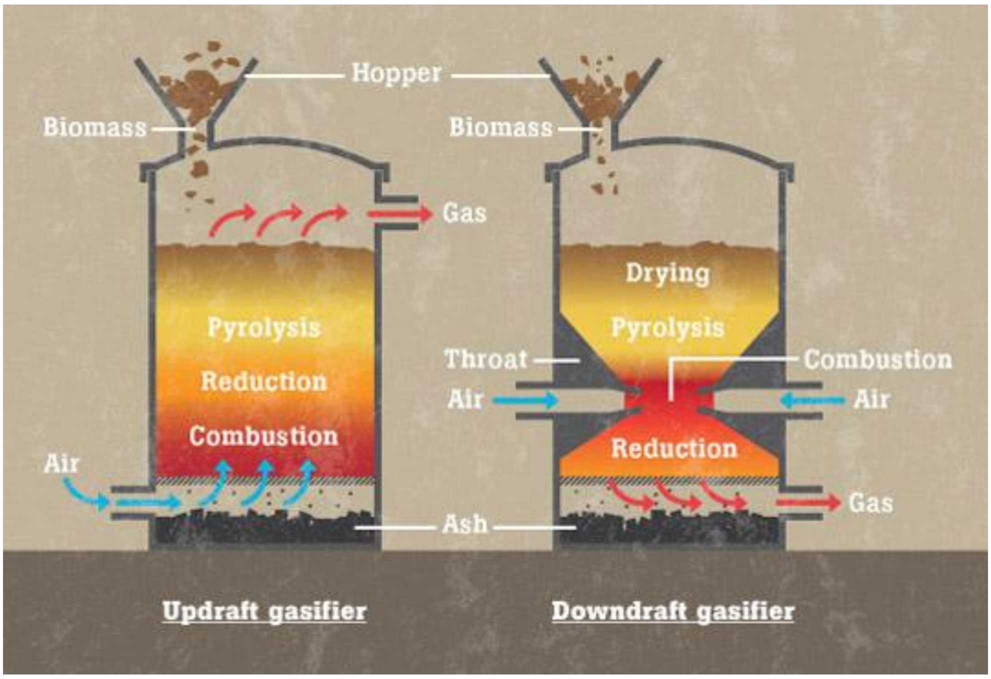

Figure 20 - Fixed bed gasification processes, Source: Ashden

Most downdraft gasifiers have a V-shaped constriction or "throat", the heart combustion/oxydation zone being the narrowest, in order to create a concentrated high-temperature zone and force though it all pyrolysis gases to crack the tars. Air is directly fed into this zone by air inlet nozzles. In recent designs, the reactor is generally double-walled. The producer gas is fed through the space between the walls, allowing an exchange of heat between the producer gas, the fuel in the pyrolysis, and the reactor drying zone. The effectiveness of this heat exchange is considerably improved with the use of small reactor diameters, which enlarge the surface of the heat exchange considerably (The World Bank, 1999).

Below are summarized a number of advantages and drawbacks related to both systems.

Updraft gasifier

- Allows sensitive heat from the produced raw gas to be used to dry the fuel and to start pyrolysis. In this manner, the raw syngas is already substantially cooled on its way through the bulk filling (while in an downdraft gasifier, these zones are only heated by radiation -and partly convection- heat from the combustion hearth zone)

- Is a multi-fuel system, less sensible to feedstock humidity (can run on higher moisture up to 30-40%) and density (down to 400 kg/m3, against a minimum of 500 kg/m3 in downdraft case) than downdraft system (can work on briquettes, coal and other fuels)
- Has easy removal of ash, so it can take raw materials which contain high ash material (< 15%) such as coal
- The main disadvantage of updraft gasifier is that the quality of syngas is comparatively low as it is having high tar and particulate matter. In fact, products of pyrolysis decomposition as well as the steam released during biomass drying are discharged directly out of the reactor with the producer gas. Problematical pyrolysis gases are thus not conducted through any hot zone and can therefore not be suitably cracked or oxidized. The tar content in the raw gas can thus reach values over 100 g/Nm^3 during gasification of the biomass, making it suitable for thermal applications only and thus inappropriate within INBAR project's framework

Downdraft Gasifier

- Has lower gasification efficiency due to the relative high temperature of the exhaust flue raw syngas (whose heat is not used in the drying and pyrolysis zones)
- But produces a syngas with low tar content which is suitable for power applications. More precisely, in this process pyrolysis products have to pass through the oxidation zone, which can be described as the "hot treatment zone for tarry compounds", and become there transformed to a great extent into stable gases. This leads to considerably lower concentrations of tar compounds in the producer gas, at an approximate load of 1 g/Nm^3 (Oettel, 1998). Downdraft gasifiers are also suitable for thermal applications where high quality of gas is required
- Still has quite a good flexibility regarding the type of biomass (any woody biomass & charcoal), as long as low moisture (< 15-20%) and quite low ash content (< 5-6%) are ensured. Too high amounts of water in the fuel don't make it possible to assure high enough temperatures in the oxidation zone, that are important for the conversion of the pyrolysis vapor and tars
- Can be subject to ash melting (vitrification) obstructing the reactor's grate and more generally, may demand higher maintenance
- Is limited in size to a few hundred kWe, which is closer to an advantage here as it perfectly applies to the INBAR project

These elements can be summarized as represented in Table 6 below:

	UPDRAFT	DOWNDRAFT
Feedstock requirements	Lower	Higher but acceptable
Efficiency	Higher	Lower
Syngas quality	Too high tar content for power applications	Lower tars and particles contents Higher ash content
Size	Adapted to large-scale	Limited to small-scale, adapted to INBAR project's needs

Table 6 - Comparison between updraft and downdraft gasifiers, Source: ENEA Consulting

In the INBAR project's context, a fixed downdraft gasifier would clearly be the relevant option in case gasification is selected as the valorization path, as the only economic option on a small-scale that also produces a fairly clean gas suitable for electricity production. Models with batch or continuous feed are available.

4.1.4 Operational performances

4.1.4.1 Efficiency

In comparison with combustion, gasification shows lower thermal losses and better energy use of the fuel. Under optimal operating conditions it is theoretically possible to attain fuel conversion rates of over 95%$_{Mass, dry}$ (Hammerer, 2000). Actually, because of secondary reactions, partial dissipation of syngas' sensible heat, and the presence of nitrogen in the gasification medium, the efficiency is inferior and the producer gas usually contains 70 percent to 80 percent of the energy originally present in the biomass feedstock.

In terms of power generation, the gasification technology is principally well suited for small power plants ranging from 10 kW to over 100 kW.

Gasification electrical efficiencies are between 20-35 %, with most small-scale applications being in the 20 % range (SPGS & Unique, 2006).

4.1.4.2 Flexibility

4.1.4.2.1 To variations in biomass quality

A more constant operation is always better. This includes feedstock quality. A change in biomass is possible as far as feedstock requirements (maximum water and ash contents, minimum density, etc.) are still respected and that quality parameters stay in the same range of values. Generally, the feedstock volumetric flow is constant that is why using fuels with too different heating value from initial design is impossible. For example, a too high rise in heating value would result in a rise in temperature within the reactor, causing ash melting temperature to be reached, which would lead to clinker formation and grate obstruction. On the contrary, "light" biomass such as rice husks can't be processed by a gasifier designed for "heavier" biomass, except if they are compacted in the form of granulates.

As far as the INBAR project is concerned, no contraindication has been identified concerning a potential switch between wood and bamboo.

4.1.4.2.2 To scale-up

Scaling up a gasifier/engine plant is difficult. For example, a scale-up from 1 to 5 MWe would result in five units of 1 MWe rather than 1 unit of 5 MWe. Therefore, if a rise in electricity production is to be anticipated for the project, the first answer would be to oversize the plant design and to run on partial load during the first year. Then, if production overpasses full load capacity, another unit can be added. Nevertheless, it has to be kept in mind that initial design and potential oversizing deeply depend on the capacity of the gasifier (as well as the associated engine) to run on partial load (see below).

4.1.4.2.3 To variations in biomass feed rate

Operation on partial load is for most gasifiers unsatisfactory. At these scales, a maximal variation of 20 to 25% from nominal capacity is conceivable, at the expense of both efficiency and gas quality. For instance, it is impossible to design a 20kW gasifier and to start the project at a partial capacity of 10kW: running with half the planned biomass feed rate would make it much harder to reach the temperatures needed for gasification reactions to occur. In this configuration, the construction of two 10kW plants would be preferable.

4.1.4.3 Main operational issues

The World Bank review of combustion and gasification technologies gives a good overview of main technical and operational problems that can be associated with fixed-bed gasifiers:

Explosions: explosions may occur when combustible gases leak through the fuel feeding system, the ash discharge system or any other leakage point. After shutdown of a gasifier, combustible gases will remain in the equipment. If the gasifier is ignited again without first venting the equipment with fresh air, the combustible gases still present may explode. To reduce such risks, gasifiers should be located in well-vented rooms or in open air. Operators should be taught about the risks of gasification equipment, especially during start-up and shutdown. Dust auto-ignition and explosion can also occur if wood chips have a too high fraction of fine wood particles (< 5mm). This fraction should not exceed 5% of the introduced biomass.

Carbon monoxide accumulation: Carbon monoxide represents around 20% of the syngas. Any leakage could lead to an accumulation of this gas around the operating area, rising danger of suffocation for technical staff. Therefore, the gasifier should be situated in a well ventilated or open-air area. A carbon monoxide sensor can also be installed, conditioning the alarm and the ventilator startup if the concentration threshold is exceeded.

Fuel blockages: fuel blockages may occur in the throat of the gasifier, caused by an inappropriate combination of fuel size and morphology, ash content, bulk density, etc. The gasifier design should be adapted to the biomass properties, as feedstock preparation and quality should be closely monitored.

Corrosion: Corrosion may be a problem, particularly in the high-temperature areas (throat). It can be caused by the combination of high temperatures and contaminants in the feedstock. Heat resistant materials can be used to answer this issue.

Tar production: even under best operation, it is impossible to totally avoid the production of tars, but more, excessive tar production may be caused by inappropriate fuel properties or during periods of variable or too partial load operation. The design of a gasifier should thus be adapted to the biomass properties also for this reason, and plants should operate at steady or full load as much as possible.

Other important points that have to be considered concerning gasifier operation (Graz University of Technology, 2007):

- Reliable performance of the fuel filling level monitoring device
- Gradual sinking of the fuel filling and prevention of dead space formation
- Homogeneous, stable reaction conditions in the respective reaction zones
- Sufficient retention times in the reaction zones
- Controlled air supply in the individual reaction zones
- Temperature and environmental stability (reduced conditions) of the reactor

4.1.4.4 Syngas quality

As said, syngas' main constituents are CO, CO_2, H_2, CH_4, higher hydrocarbons, N_2, and impurities.

The main focuses concerning the gas are on its quality (calorific value, composition, amount and type of impurities) and its generated quantity.

4.1.4.4.1 Influence of gasifying medium on syngas heating value

If air is used as gasifying medium, the produced syngas has a low calorific value (4-7 MJ/m^3) due to its dilution by nitrogen (in excess of 50 %) and other incombustible components.

Gasification by means of oxygen-enriched air or water steam as gasifying medium, gives rise to medium calorific gas with heating value around 10-15 MJ/m^3 (Bridgewater, 1995). But as the use of oxygen for gasification is expensive, air is normally used for processes up to about 50 MW (Laurence & Ashenafi, 2011).

As a comparison, the calorific value of natural gas is about 30-40 MJ/m^3 (GTZ, 2010).

4.1.4.4.2 Influence of biomass humidity on syngas composition

Typical composition of syngas is shown below:

Gas	CO	H_2	CH_4	CO_2	N_2
%vol (dry)	20	15-18	3	10-12	rest

Table 7 - Average syngas composition, Source: ENEA Consulting

But as shown in the graph below, feedstock water content has an impact on the syngas composition, increasing non-flammable CO_2 at the expenses of flammable CO, thus decreasing the syngas calorific value and the quantity of energy than can be ultimately recovered from the same amount of biomass.

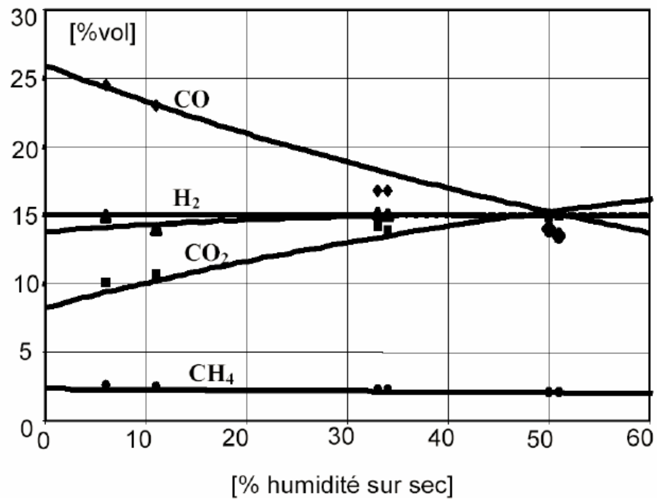

Figure 21 - Syngas composition against biomass humidity content, Source: UCL/TERM

This is a good illustration of the important need for inspection of the biomass quality, from delivery to feeding. More generally, biomass storage, transport and feeding have an important influence on the quality of the fuel itself, as well as on the process stability (e.g. producer gas quality, stability of heat and power production, etc.).

4.1.4.4.3 Influence of application on syngas specifications

Gas quality specifications – especially the cleanliness – depend on the application.

For heat-only production, the producer gas can be immediately burnt without modifications in gas temperature or contaminants.

For the production of electricity or mechanical power, the gas has to be cooled, for some applications pressurized, and most importantly cleaned. The high-temperature combustion step already refines out corrosive ash elements (chloride, potassium). Therefore, the main issue to syngas use in an internal combustion engine is the removal of dust (airborne particulates), tarry product (i.e. all organic compounds with boiling point above that of benzene, i.e. 80.1°C ; (Neft, 2002)), ash and corrosive gaseous compounds (e.g. alkali compounds, nitrogen compounds, sulphur compounds).

The content of such impurities in the gas causes operation problems to the units due to clogging and tarring of working surfaces of engines (gas supply lines, gas air mixer, intake valves, etc.), which may lead as far as serious damage to the equipment under operation. Particularly, any tar accumulated on valves or valve stems will harden during cooling and prevent the valves from closing. Also, acids may cause severe corrosion and affects the lubrication properties of the oil (The World Bank, 1999).

But most of all, tar and dust are the most critical factors limiting the use of fuel gas.

Table 8 gives additional details on the syngas composition's expected specifications for different power generation devices, to be compared with the raw syngas composition. The latter is also indicated in the table, using quite large value ranges as raw syngas composition deeply depends on each technology provider, biomass composition and operating conditions.

	Tars mg/Nm³	Dust particles mg/Nm³	Alkali mg/Nm³	NH_3 mg/Nm³	Chlorides mg/Nm³	Sulphures mg/Nm³
Raw syngas	**10-1000**	**100-1000**	n.a	n.a	n.a	n.a

(air-blown downdraft)	**(mean 500)**	**(size < 10 µm)**				
			Applications			
Boiler	**-**	**-**	-	-	-	-
Gas engine	**< 50-100** **(if possible < 25)**	**< 50** **(if possible < 5)**	< 1	< 50	< 10	< 100
Gas turbine	*< 5*	*< 30*	*< 0.24*	*~ ppmv*	*~ ppmv*	*~ ppmv*
Fisher-Tropsch	*< 1*	*< 0.02*	*~ ppmv*	*~ ppmv*	*~ ppmv*	*~ ppmv*
Fuel cell	*< 1*	*~ ppmv*	*~ ppmv*	*~ ppmv*	*~ ppmv*	*~ ppmv*

Table 8 - Syngas specifications for various applications, Source: ENEA Consulting, adapted from CIRAD

Therefore, gasification does not only entail the production of gas but also its treatment (Skála, 2003).

Gas treatment requirements and techniques are described in the following paragraph.

4.1.5 Syngas treatment

There are various technologies used for synthesis gas cleaning depending on the specific clean up requirements. Here, treatment options are discussed regarding the use of a gas engine to produce electricity.

The systems are differentiated according to the following factors (Graz University of Technology, 2007):

- Pollutant fraction in the process gas (dust, tar, heavy metals, alkali- or alkaline, earth metals, permanent pollutant gas, etc.) to be eliminated
- Process media (dry, wet, half-dry, etc.)
- Separation mechanisms
- Operating temperatures and pressures
- Separating efficiency

Conditions for gas cooling and cleaning are defined by both the inflowing producer gas and the requirements of downstream equipments. Economic considerations are also a key factor to choose and design the adequate treatment option, particularly in the case of small-scale units for which low cost are essential.

4.1.5.1 Cooling

The producer gas leaving the gasifier is at a high temperature, around 700° C (500-800° C).

The purpose of gas cooling is to lower the syngas' temperature in order:

- To fulfill the following gas treatment equipment requirements and ensure their optimal operation.
- To fall below the syngas' dew point in order to condensate as much tarry compounds and water vapor together with dust as possible

In demonstration facilities the reactor discharge (500-800° C) is cooled down to a level of about 100-600° C, to be able to carry out dry particle filtration with fabric filters or ceramic filters respectively (Graz University of Technology, 2007).

For power generation, a temperature inferior to 40°C is required to optimize the volumetric efficiency of the gas engine. Therefore, adequate cooler and chillers have to be installed.

4.1.5.2 Dust particles removal

Gas cleaning has the task of de-dusting the producer gas as well as ensuring suitable purity regarding tar load. It also ensures a feed of constant gas quality to the gas engine, independently of potential fluctuations in the raw syngas quality.

There are two main types of cleaning equipments: wet and dry.

4.1.5.2.1 Wet gas cleaning

Wet gas cleaning systems use a liquid scrubbing agent to wash and purify the syngas, using the adherence and dissolving property of the contaminants in the liquid.

These cleaning methods also have a cooling effect because of the heat exchange between the syngas and the scrubbing liquid.

Scrubbing liquids that are commonly used are water, water/oil emulsion, condensates and various hydro-carbons. The most commonly used wet scrubbers are spray towers and scrubbers, sieve plate scrubbers, venturi scrubbers and packed bed scrubbers (Laurence & Ashenafi, 2011).

Wet scrubbers are widely used to clean and cool the gas, especially in stationary applications, showing the best cost/efficiency ratio. Nevertheless, a major drawback of direct water-based systems is the tar-contaminated waste water stream which needs treatment before disposal (otherwise causing severe environmental damage) or recycling to form a close water loop.

Example of water treatment plant associated with wet gas cleaning:

Impurities are in two different forms: soluble (tars) and insoluble (suspended particulate matters, SPM).

Particles can be simply separated by decantation. Sedimentation can be made easier and quicker (30-45 min) by the addition of chemical (coagulant or flocculant). Indicated products' quantities are 40g of flocculant and 10 mL of coagulant by waste water square meter given a SPM content of 1500-2000 mg/L (UEMOA, 2008).

Tars can then be extracted using activated coal, or part of the produced (and free) charcoal after being powdered.

Figure 22 and Figure 23 show Ankur Scientifics' installation and illustration of water quality along the treatment process.

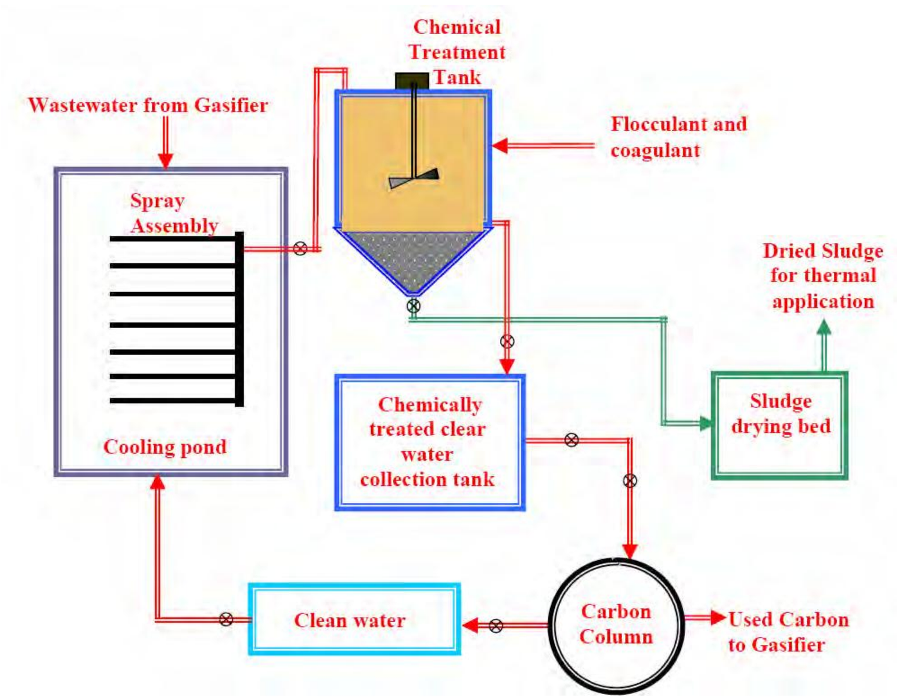

Figure 22 - Water treatment flow diagram, Source: Ankur Scientific

Figure 23 – Water treatment plant and water quality along the process, Source: Ankur Scientific

The estimated water treatment losses are 3%-5% per day and this has to be compensated.

But more important, the remaining sludge has to be disposed appropriately, which is usually not the case.

4.1.5.2.2 Dry gas cleaning

Dry gas cleaning includes quite common technologies already used to clean combustion flue gases, such as cyclones (centrifugal separation), sand bed filters, active coke beds, and other filters that can themselves be divided into two categories: hot gas filters and fabric filters, such as represented in Table 9:

Type	Heat-resisting filters	Fabric filters
Operation temperature	Above 500°C	Below 200°C
Typical integration	Before gas cooling	After gas cooling
Typical syngas application	Gas turbines and fuel cells	Internal combustion engines
Typical filter elements	Porous ceramic, sinter metallic materials	

Table 9 - Dry gas filters categories and applications, Source: ENEA Consulting

Cyclones and heat-resisting filters are adapted to high temperatures and can therefore be used before any cooling, that is why cyclones are usually recommended as a first cleaning step (Leibold et al., 2008).

During dust removal, syngas temperature control is essential:

- A too high temperature would damage filter units
- A too low temperature would lead to excessive tar condensation (375-400°C) that can cause operational malfunctions due to difficulties to regenerate the filter surface. Another solution is to have particles and tars removed simultaneously (see below).

4.1.5.3 Tar removal

First of all, it must be pointed that the best way to remove tars is to avoid producing them. Optimizing operating parameters such as temperature, pressure, residence time decreases tar content.

Above 600°C, tars will begin to be thermally cracked. For example, Navarpaez experimented respective 19 and 5 g/Nm^3 tar contents at 700 and 800°C.

These design considerations are absolutely essential, before any reflection on tar removal technologies.

Apart from optimizing operating parameters, current state of the art tar removal technologies could be broadly classified into four groups:

- Mechanical methods : cyclone, filters, granular beds, rotational particle separator (RPS), electrostatic precipitators (ESP) and scrubbers
- Catalytic cracking (800°C)
- Thermal cracking (> 1200°C)
- Plasma methods

Catalytic cracking, thermal cracking and plasma cracking are not mature technologies and clearly economically unattractive for small scale gasifiers.

Mechanical methods, including scrubber, filter, cyclone and electrostatic precipitators, are primarily used to capture particles. But they are also considerably efficient in removing tars, as can be seen in Table 10 below.

Method	Type	Temperature range (°C)	Particle removal (%)	Particle removal (µm)	Tar removal (%)	Investment cost* (k€)
Cyclone	Dry	100-900	80	> 5		
Sand bed filter	Dry	10-20	70-99		60-97	42
Wash tower	Wet	50-60	60-98		10-25	
Venturi scrubber	Wet	20-100	85-95	0.1 – 1	50-90	115
Wet ESP	Wet	40-50	> 99		0-60	157
Fabric bag filter	Dry	60-250	70-99	> 0.3	0-50	89
RPS	Dry		85-90		30-70	73

Table 10 - Tar and particle removal efficiency of some mechanical methods, Source: Han & Kim (2008), Guan et al. (2008), Hasler et al. (1998), Laurence & Ashenafi (2011)

**** Investment costs are given for a 300 kW fixed bed biomass gasifier including waste treatment.***

Dry ESP are not considered here, as they are not recommended for biomass syngas cleaning due to the possible condensation of heavy fractions of tar and a significant carbon content causing an increase of electric conduction and a reduction of dust removal efficiency (Stanghelle et al., 2007).

It also must be noted that, even if those pollutants are not critical to gas engine valorization, sand bed filters have the advantage to also abate NH_3 (> 95%), HCl (90%) and H_2S (80-95%) contents. They also are less sensible to partly sticking particles.

4.1.5.4 Conclusion on gas treatment

Considering a 20 kW fixed bed gasifier designed to allow electricity access to a remote rural area, the objective would be to select the most robust, less technological and cheapest combination of cleaning equipments able to meet the gas engine requirements.

The strongest advice would be to avoid wet solutions as much as possible, in order to limit additional waste water treatment.

Laurence & Ashenafi (2011) propose a combination adapted to 20 kW fixed bed gasifiers, consisting in the association of a heat exchanger, a cyclone, a quench water cooler and sand beds, as represented in Figure 24.

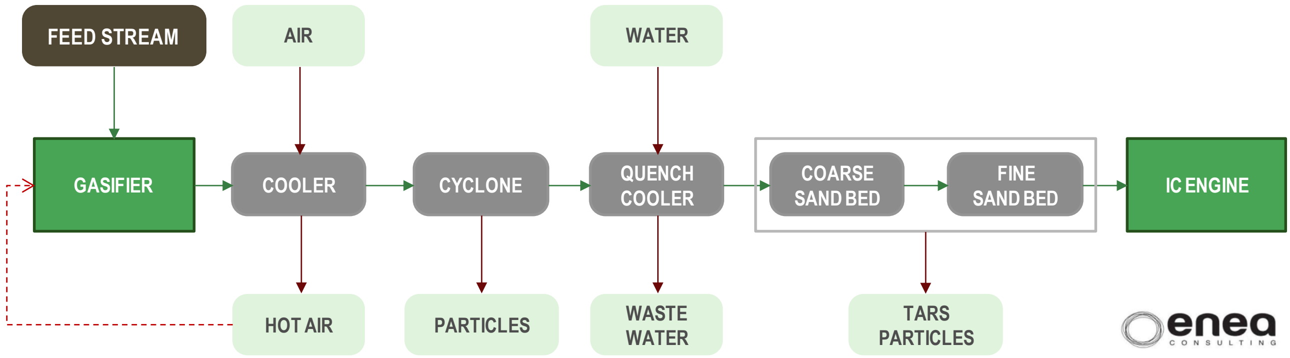

Figure 24 - Syngas treatment flowsheet, Source: ENEA Consulting, adapted from Laurence & Ashenafi, 2011

Syngas is first taken to an air heat exchanger to be cooled from a temperature of approximately 600°C to 450°C. The heat recovered from the cooler can be used to preheat the air used in the gasifier. This cooling also facilitates removal of alkali vapors with the dust particles. The temperature of 450°C is chosen to avoid tar condensation (375-400°C) in the heat exchanger and cyclone.

The cooled synthesis gas is then fed into a cyclone which removes more that 80% of particles having a diameter of more than 5 µm. The reduction of the synthesis gas temperature to 450°C will also improve the separation efficiency of the cyclone in addition to decreasing its cost.

Then the partially cleaned syngas from the cyclone is quenched by water injection before it enters the sand bed filter. The syngas is cooled in the quench cooler from 450 to 250°C to condense some of the tar and keep the syngas temperature in the operating temperature range of the sand bed filter.

Finally the gas is fed to a two stage sand bed filter. According to Hasler and Nussbaumer (1999), the clean gas will leave the dual layer sand bed filter at a temperature of 5 to 25°C. This can in practice be fed directly into an internal combustion engine since it operates at room temperature.

This system has the advantage to be simple, efficient and relatively cheap. However, this may not be the only option and if a totally dry combination would be preferable.

4.2 Electricity generation through internal combustion

Once the syngas is duly cooled and cleaned until reaching the gas engines' specifications reported in Table 8, electricity can finally be generated, provided a minimum acceptable syngas Heating Value of 2,5 GJ/Nm^3 (values superior to 4,2 GJ/Nm being preferable).

In practice, internal combustion piston engines are almost exclusively used for the small-scale applications discussed here, either to produce mechanical power (to action an irrigation pump for instance), or else to drive an alternator and generate electricity. Apart from some minor adaptations, this generator set is more or less the same as used with other fuels.

4.2.1 Internal combustion engines

There are two types of internal combustion engines that can use clean synfuel:

- Spark ignition "Otto" engines
- Compression ignition "diesel" engines

Figure 25 – Example of a 35kW gas engine, Source: Husk Power

4.2.1.1 Diesel engines

First, it is possible to operate some diesel engines on dual fuel mode with marginal changes to the air inlet. The engine draws anything between 0 and 90% of its power output from producer gas, the remaining diesel oil being necessary for ignition of the combustible gas/air mixture. Ignition spray is varied depending on the output requirement of engine management and the processed syngas quality and thus serves in part as a backup against engine failure in case of fluctuations in syngas quality (Graz University of Technology, 2007). Diesel engines can also be converted to full producer gas operation by lowering the compression ratio and the installation of a spark ignition system.

But not all types of diesel engines can be converted to the above modes of operation. Compression ratios of ante-chamber and turbulence chamber diesel engines are often too high for satisfactory dual fuel operation and use of producer gas in those engines leads to knocking caused by too high pressures combined with delayed ignition (FAO, 1986). Direct injection diesel engines have lower compression ratios and can generally be successfully converted.

Diesel substitution of the order of 75 to 90% can then be obtained at nominal loads in the dual fuel mode (Bambotech; SPGS & Unique, 2006). In general, a minimum of 7 % diesel is needed. If syngas is not available the engine can alternatively operate on 100% diesel.

The maximum power output of a diesel engine running on syngas depends on the gas heating value, quantity of diesel fuel injected and specific engine characteristics. Comparing to the same engine running on full diesel fuel mode, the efficiency of the dual-fuel mode is up to 25% lower (The World Bank, 1999 ; SPGS & Unique, 2006). Moreover, the diesel engine efficiency after conversion to a spark-ignited engine can show as much as 45% lower efficiency compared to the original diesel engine (The World Bank, 1999).

To be noted that Husk Power Systems has recently commercialized a 35 kW compression-ignition engine that is announced to run on pure syngas and said to provide power to about 500 households and small businesses through a local grid.

4.2.1.2 Spark ignition engines

Contrary to diesel engines that generally need co-fuelling of conventional diesel fuel, spark ignition engines can entirely run on syngas.

Having a good mixing between air and fuel is important, often achieved thanks to a T-shaped mixer, associated with a control system ensuring a constant gas/air ratio.

The maximum power output expected from an Otto engine running on syngas depends on the gas heating value, the ignition timing and specific engine characteristics, but remains usually lower than when running on fossil fuel.

Wood fuel gasification systems in combination with Otto engines show overall system efficiencies (energy in the fuel/electrical energy produced) from 16 to 19%.

By integrating gasifiers in combined heat and power systems (CHP) their efficiencies can rise significantly, but in a first approach with no additional data on the project's economical environment, we will not consider an external heat use as a possibility.

4.2.2 Conclusion on power generation

The following table gives a brief summary of previously discussed advantages and drawbacks of both types of internal combustion engines:

	Advantages	Drawbacks
Gas Otto engines	▪ No need to import fossil fuels ▪ Higher environmental performances	▪ Higher need for syngas constant quality
Diesel pilot ignition engines	▪ Higher efficiency ▪ Higher flexibility to syngas quality change	▪ Dependency to fossil fuels ▪ Higher pollutants emissions ▪ Need for conversion to spark-ignition

Table 11 - Main advantages and drawbacks to Otto and diesel engines, Source: ENEA Consulting

Compression ignition engines (modified diesel engines) can have higher efficiency and flexibility to syngas quality but cannot run on syngas alone. From an environmental point of view, gas Otto engines allow to not use fossil fuels and lead to comparatively lower emissions.

Moreover, the possibility for diesel engines to run on a 100% fossil fuel basis may be seen by local community as an easier alternative and a lack of incentive for sufficient efforts needed for the gasification plant to run successfully.

As a conclusion, we would recommend an ignition-fired "Otto" gas engine for this project.

4.3 Environmental impacts

A biomass gasification facility can impact its environment at several levels, mainly:

- Through the explosive mixture of toxic and combustible gases that syngas represents, as well as trough the results of its combustion
- Through residual substances generated by the process.

As far as flue gas emissions are concerned, the following components can be expected in the engine's exhaust gas, and thus to be vented to the atmosphere:

- Carbon dioxide (CO_2)
- Oxygen (O_2)
- Carbon monoxide (C_O)
- Organic hydrocarbons (C_xH_y)
- Nitrogen oxides (NO_x)
- Nitrogen (N_2)
- Steam (H_2O)
- Trace elements of organic and inorganic substances

Considering the very small scale of the plant, in addition to the fact that these emissions are lower than those of a classical fossil fuel diesel generator (and lower than an equivalent combustion / steam cycle's ones), exhaust gas should not be a problem.

Noise pollution is low. A gasifier almost runs in silence, while gas engine is not noisier than a classical diesel one (around 100 decibels for a 250 kW engine running at full capacity, which is equivalent to a big truck).

Thus, residues generated in combination with gas production, gas cleaning and potential wastewater treatment, which are then extracted, converted and recycled, clearly remain the main environmental issue and adequate disposal measures have to be implemented.

5 Comparison of main valorization scenarios

To sum up technological presentations that have been developed in the previous sections, and give a basis to comparative discussion, Figure 26 below summarizes both paths' general process flows being compared in this study.

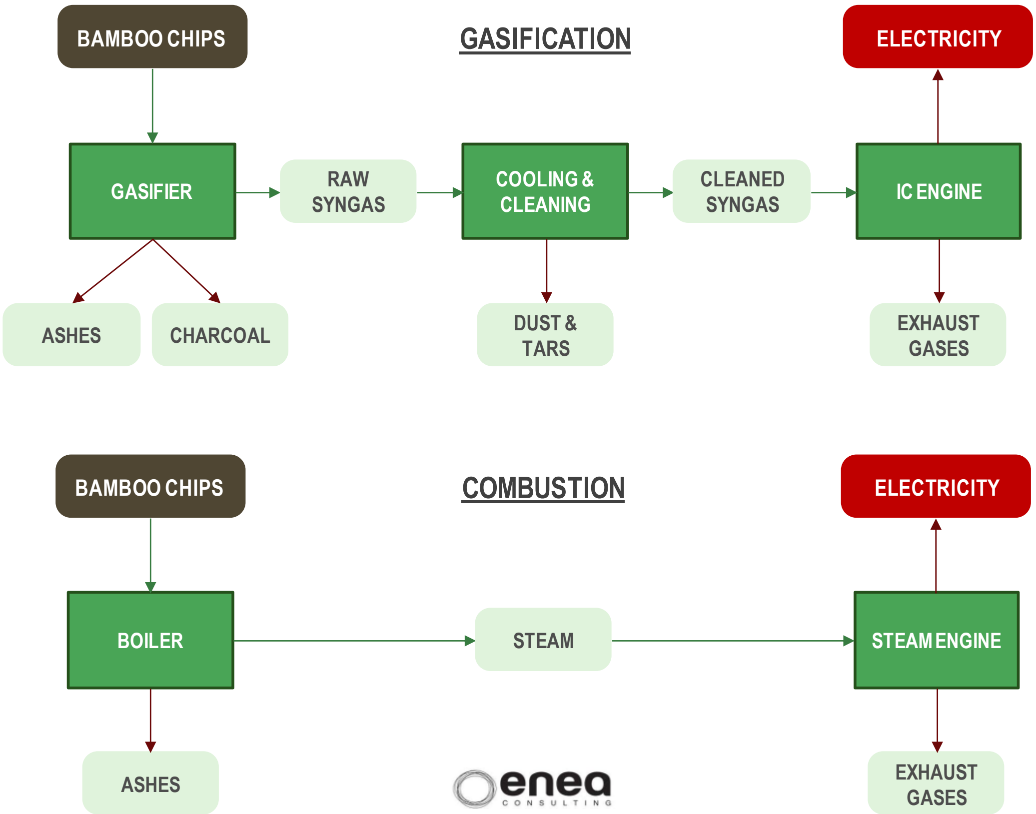

Figure 26 - Comparison of gasification and combustion general process flows, Source: ENEA Consulting

The choice of the technological path will have direct impact on critical project parameters, such as:

- Energy generation potential from a given amount of bamboo (or necessary quantity of bamboo to face a given need for electricity)
- Type of process outputs, ability to generate recyclable and valuable products
- Commercial status, maturity, scale and risk factors
- Environmental impacts
- Economic viability of the project : capital and operating expenditures, which has impact on the price of electricity and final social impacts of the project

Table 12 provides a summary of main information needed to compare combustion and gasification paths, and more particularly in terms of:

- Choice of technologies
- Feedstock requirements
- Operating conditions
- Environmental impacts

	COMBUSTION PATH	GASIFICATION PATH
GENERAL INFORMATION		
Primary energy convertor	Boiler	Fixed Downdraft Air Gasifier
Power generation equipment	Steam engine	Otto engine
Main thermo-chemical reaction	$C + O_2 \rightarrow CO_2$	$C + H_2O \rightarrow CO + H_2$
FEEDSTOCK REQUIREMENTS		
Size (mm)	More flexible	20 - 50
Humidity (% wb)	< 60	< 15 - 20
Ash content (% db)	< 15	< 6
Ash melting point (°C)	-	> 1250
Density (kg/m^3)	-	> 500
Limit of Heating value (kcal/kg)	< 3000	> 3000
OPERATING CONDITIONS		
Air (O_2) requirement	Excess of air	Default of air
Operating temperature (°C)	> 850	750 – 1200
Operating pressure (bars)	Combustion stove : 1 (ambient) Steam : 10 – 20 bars	1 (ambient)
Overall system energy efficiency [electricity/biomass fuel] (%)	13 - 14	16 – 19 (18)
Ramp-up time	15-30 min	1-2 h
Main operating risks	Steam overheating, Blow-up	Explosion, CO leakage (asphyxia), Tar accumulation, Corrosion
Monitoring requirements	High	Very High
Maintenance requirements	Medium	Very High
Expected lifetime (years)	20-25	10-15
REACTION PRODUCTS		
Charcoal production (kg/day)	-	30
ENVIRONMENTAL IMPACTS		
Avoided CO_2	[To be calculated]	[To be calculated]
Main environmental impacts	Flue gas emissions	Syngas cleaning residues
Main flue gas contaminants	NOx, Sox and dust	NH_3 and H_2S
Ashes produced (% of feed bio-mass weight)	5	0.5 - 1
Noise pollution	Inferior to a diesel generator	Same as a diesel generator

Table 12 – General technical and environmental comparison between valorization paths, Source: ENEA Consulting

Apart from purely technical considerations, it is then important to determine which technology provides the optimum cost-benefit delivery for the specific application of this project.

Economics involved in designing a bioenergy system are complex, and detailed calculations can only be carried out for a specific case because depending on the specific energy need profile, the selected technology, the operational environment, the local regulations, among others.

Nevertheless, rough calculations for generic scenarios can give project leaders and potential investors a clearer understanding of the main parameters involved in the financial dimension.

The investment costs for a gasification plant vary significantly. Various data from Sri Lanka to European countries indicate range from 150 €/kW to 4,000 €/kW, but it is likely that the cheap gasifiers from local production require far more maintenance and that these costs are often not documented and calculated correctly (GTZ, 2010). Feedback from specialists show that the order of magnitude of capital expenditures for small-scale gasifiers that one can expect to show acceptable reliability is no less than 1500-1700 €/kW. A very preliminary investment cost assessment for a 20 kW gasification plant would thus be around 30 000 €.

To be noted that GEK, an "experiment in collaborative science and open source engineering, in which volunteering participants are working together to advance the science of gasification, and the engineering solutions to implement it meaningfully for today's users", now propose very interesting integrated 10 kW and 20 kW power pallet at respective capital costs of 17 and 26 000 US$, i.e. down to 1000 €/kW. French CIRAD has planned to buy one to test it for its rural electrification project in Peru. Appendix 2 provides a more detailed presentation of this product.

Investment costs for combustion are higher (and volatile as well), superior to 2000 €/kW. This is due to several parameters, including:

- Higher equipment costs: ratio between total plant cost and equipment cost is higher, because of the higher complexity of the process
- Higher infrastructure costs: a steam boiler being much heavier than a gasifier, and a steam engine implying louder vibrations than gas engine, thicker concrete foundation are needed

A very preliminary investment cost assessment for a 70 kW combustion plant would thus be around 140 000 €.

The Indian Institute of Science also estimated the cost of generating electricity via biomass gasification (2007). Running costs for gasification were estimated at about US$ 0.05 per kWh generated. Similar costs were estimated for China. But these data must be manipulated with the highest precaution. Operating costs are so variable that it is quite impossible to determinate without all details on chosen providers and the local context.

Operating costs structure is mainly composed of the following elements:

- Feedstock costs
- Feedstock transport
- Feedstock preparation
- Gas treatment
- Residue disposal
- Maintenance costs
- Labor

To evaluate the economical viability of a project, these costs are to be compared to the various sources of revenue, such as:

- Revenue from electricity services
- Revenue from biochar (gasification and pyrolysis)

- Revenue from carbon credits

	COMBUSTION PATH	GASIFICATION PATH
Efficiency	Lower efficiencies (10-15%)	Efficiencies between 20-25%
Maturity and robustness	Combustion is a proven and simple technology Steam engines are relatively robust technology	Gasification still needs to be proven in long-term operation: poor to reasonable reliability Gas engines are robust and widespread
Complexity	High	Moderate
Operability	Quite simple. Still, boilers need close monitoring and maintenance	Quite difficult: dedicated and skilled engineering support needed
Flexibility: ***to change in biomass*** ***to change in load***	Higher flexibility	Lower flexibility
Start-up / Shutdown	1 – 3h	0,25 - 0,5 h
Safety	High-pressure steam	CO release
Environmental impacts	Flue gas emissions	Low level of NOx emissions Tar disposal (waste water pollution)
Investment costs	Higher investment costs	Lower investment costs
Expected lifetime	20-25	10-15
Operating costs	Lower costs per unit of electricity	Higher costs per unit of electricity High fuel and maintenance costs

Table 13 – General comparison of combustion and gasification paths, Source: ENEA Consulting

6 Integration within INBAR project and local environment

6.1 Bamboo consumption

Depending on the valorization path and target in electricity generation, different quantities of bamboo will be needed and crop surfaces secured. This section's objective is to assess these quantities, summarized in table13..

Calculations are based on the following assumptions:

- **Bamboo biomass characteristics:** LHV, water content and crop yield are those that have been provided by INBAR for Yushania alpine.
- **Power needs**: reflection is firstly based on INBAR's input i.e. bringing around 3h of electricity to a hundred of household having an average consumption of 0,15 kWe each. Nevertheless, based on previous conclusions concerning technologies (minimal power application of 70 kWe for steam cycle, etc) and potential presence of economical activities (bamboo furniture's manufacture, irrigated agriculture, etc), half-day production scenarios were also assessed.
- **Plant availability**: a mean availability of 80% has been taken for the plants, including maintenance and unexpected shutdowns, representing 330 days of production a year.

	Unit	Combustion 70kW 3h/day	Combustion 70kW 12h/day	Gasification 20kW 3h/day	Gasification 20kW 12h/day	Pyrolysis 12h/day
Daily electrical need by household	kWhe			0,15	0,15	0,15
Number of targeted households	-			100	100	100
Total annual need for 100 households	kWhe	69 300	227 200	14 850	59 400	59 400
Primary energy conversion efficiency (steam / syngas)	%	90	90	80	80	40
Engine efficiency	%	15	15	25	25	25
Needed annual primary energy in bamboo	kWh	424 286	1 980 000	74 250	297 000	594 000
Needed annual primary energy in bamboo	MJ	1 527 429	7 128 000	267 300	1 069 200	2 138 400
Bamboo Low Heating Value	MJ/kg_{DM}	13	13	13	13	13
Needed bamboo weight / year	t_{DM}	137	548	21	82	164
Bamboo water content	%	12	12	12	12	12
Needed bamboo weight / year	t	156	623	23	93	187
Bamboo consumption	Kg/kWhe	2,2	2,2	1,6	1,6	3,2
Bamboo feed rate	kg/h	157	157	24	24	47

Bamboo yield	t_{DM}/ha	80	80	80	80	80
Needed bamboo crop yielded surface	ha	1,71	6,85	0,26	1,03	2,06
Needed bamboo crop total surface (20% older plants	ha	8,57	34,27	1,29	5,14	10,28

Table 14 – Bamboo needs (consumption, feed rate and surface) for different scenarios, Source: ENEA Consulting

6.2 Logistical integration of the plant

6.2.1 Biomass collection and transport

It is important to have a good assessment of biomass availability for the energy production unit, both in space and time.

This encloses the following parameters:

- Distance from bamboo cultures to electricity generator, which has to be minimized for both economical and environmental points of view
- Harvest periods
- Delivery times and frequencies, which depend on transport capacity, quantity of biomass needed, volume and conditions of biomass on-site storage, or else possible annoyances to close residents (noise, dust…)

Contracts have to be made with the bamboo producer / project partner for an uninterrupted supply of biomass to the plant. As well, contract (or agreement) should include guarantees related to the quality of bamboo, both in terms of humidity content not to be exceeded, and in range of calorific value to stick to.

6.2.2 Storage area

Biomass storage includes the area of delivery and unloading, as well as potential treatment (drying) during the storage period. The amount of biomass to be stored depends on the respective configuration of the plant (performance range, fuel logistics, and plant operating state). Depending on local climatic conditions (hygrometry, etc), storage system may consist of a simple shelter or a storage silo with a screw to force the fuel out.

Besides biomass storage it is also necessary to pay attention to the storage of other process utilities such as potential auxiliary fuels for various co-combustion purposes, lubricating oils, water, gas cleaning products, and residues from plant operation (Graz University of Technology, 2007).

Result of both delivery logistics and storage capacity will determine the degrees of autonomy and flexibility of the plant as well as its capacity to be operated with a stable load of power.

6.2.3 Fuel feeding

Feeding fuel into the boiler or gas generating reactor is normally done by means of clocked conveyance systems activated by the output regulation of the entire system. Fuel feeding has to be carried out via a gas-tight transfer canal that prevents gas leakage and the aspiration of excessive amounts of leakage air. Depending on the grain size of the fuel to be transported, the following transport systems are used:

- Belt conveyor
- Chain conveyor or trough chain conveyor, respectively
- Screw conveyor
- Vibrating conveyor for dosing into the transfer system

- Stop valve transfer system
- Squeeze valve system
- Rotary valve system
- Double sluice system

Important points that have to be considered (Graz University of Technology, 2007):

- Gastight fuel feeding system regarding positive and negative pressure
- Reliable performance of the filling level monitoring device

6.2.4 Residual waste handling

Fly-ash and dried sewage fertilization has been shown feasible for bamboo and some other trees/shrubs could be used by the bamboo growers on their fields. Actual impact on earth fertility can be limited with this type of biomass, but must not be disregarded. Moreover, this could result into people enhanced confidence on bamboo (Native Power Private Ltd, 2011)

Ashes, if there are any related activities around, may also be reused in construction (brick manufacturers, roads, etc).

In the case of gasification, sludge from gas cleaning also has to be taken care of.

6.3 Electricity use and associated business model

Last but not least, the type of electricity supply must be adapted to the needs and it must be acknowledged that wire-pulling is not the only solution. Investment costs can rise very quickly (8000 €/km), then if the power need is equivalent to only one or two 15W lamps three hours a day, building a wire to each household would probably not be the most suited solution.

Other systems can be set up, such as "electrical blocks" distributed over the village or town center. These blocks gather streetlights, free plugs or even shared electrical devices such as a fridges or radios. These little electrical centers can be backing to key social places such as schools or any other place where people are used to gathering, enhancing activities and social exchanges around these spots. This also limits the number of wires to be pulled and associated expenditures.

A battery rent activity can also be built, charging batteries in the morning with a certain amount of energy and having people paying for a one or two days renting (depending on consumption and battery capacity). This system implies much lower capital expenditures than a micro-grid (recharging system costs a few hundred Euros, and 100 batteries of 50 Ah cost around 1500€) and allows power generator to run on a much more stable and controlled basis.

As for the choice of technology, type of electricity supply would depend on the quantity of electricity to provide and types of local uses. Table below sums up potential associations between these parameters:

	COMBUSTION PATH	GASIFICATION PATH
Type of electricity need/use	▪ High load constant power production from 70 kW upward ▪ Bring light to 100 households + economical activities with constant needs ▪ Micro-grid to connect businesses and electrical blocks	▪ Flexible power production from 20 kW upward ▪ Bring light to 100 households (+ possible reduced economical activities) ▪ Micro-grid to electrical blocks, or battery / lamps renting system

Table 15: Valorization paths, electricity needs and electricity supply, Source: ENEA Consulting

Conclusion

Main barrier to implement bamboo gasification and combustion systems in Rwanda is the lack of experiences and real data from a pilot project. Experiences in Europe, but also in India and Brazil, demonstrate that both technologies can work, with very heterogeneous degrees of success.

Combustion process using a steam engine is reliable but can only be used for high load constant power production from 70 kW upward. This option would be preferable provided higher power needs than currently anticipated.

Gasification process using a gas engine is more adapted to very small production scale but has poor reliability and need very dedicated and skilled operators. An important number of projects that have been launched in the past stopped and this option is obviously not without risks. Opting for this valorization path would necessitate appropriate support from experienced entities, and sufficient subventions would need to be found to cover financial risks.

Surface assessment showed that 1 or 2 ha of bamboo a year would be sufficient to supply the power plant. Considering that all bamboo culms are not harvested at the same time but the oldest 20%, 5 to 10 ha would be needed.

Necessary contextual data to collect before going any further:

- What are actual local individual needs for electricity ?
- What are the local economical activities ?
- What is the population concentration ? How dense / scattered ?
- Are people ready to pay for electricity ? How much ?
- Are there areas with people already using electricity (diesel generators…) ? What is the price for a kWh of electricity ?
- What are the fuels currently used for cooking ? Is there a market for charcoal ?

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Appendix 1 : Experience feedback from three small-scale gasification projects

Saran Renewable Energy, India

6.3.1.1 Project background

Saran Renewable Energy (SRE) was set up by a family-owned grain-trading business, because of concern about the lack of electricity in Bihar. SRE has built a biomass gasification plant at Garkha to gasify biomass bought from local famers, and use the gas to generate electricity, which is sold to small, local businesses.

The project started in 2006.

6.3.1.2 Technology

<u>Biomass</u>

Supply

Locally supplied biomass is used as the fuel for the gasifier. The main source (about 70%) is from a native woody plant called ‘dhaincha’ which grows rapidly in swampy areas, and also on uncultivated land beside roads and rivers. The remainder is from a variety of sources like corn cobs, wood, and other local plants similar to dhaincha. Biomass is sold to SRE by the farmers who produce it.

Preparation and storage

SRE staff chop the long stems of dhaincha and logs of wood into pieces 50mm long, and these are dried in the sun to a moisture content of approximately 15%. The biomass is stored under cover in the building housing the gasifier. This building is well ventilated to prevent the buildup of poisonous or explosive gases.

An adequate stock-pile of fuel is stored on site to prevent shortages but fuel is always.

<u>Gasifier</u>

SRE chose a **down-draught open-top gasifier**, manufactured by **Netpro** under license from the Indian Institute of Science (IISc) in Bangalore.
Biomass is fed into the top of the reaction vessel every 15 minutes. Air is drawn through at a controlled rate, to provide oxygen for the gasification process and dry the biomass.

Syngas cleaning

Initially, a **cyclone separator** spins out solid particles and a **water scrubber** absorbs other impurities. Then the gas is cooled to below 100°C so that it does not overheat the engine. A fabric filter removes any remaining particles prior to the engine. The IISc gasifier design produces very low levels of tar and particulates, which has the dual benefit of low emissions and low plant maintenance. The cleaning water is initially taken from a borehole. After use, it is pumped into a large tank and treated chemically before being reused.

<u>Generator</u>

The generator used is a **dual-fuel** Kirloskar engine made in Pune. It supplies **128 kW** of electricity at 240 V.

The plant runs for 11 hours a day (from 10:00 to 21:00) and supplies about 220 MWh per year. It saves an estimated 0.35 liters of diesel per kWh, or about 77,000 liters of diesel per year.

6.3.1.3 Customers

The generator is connected to a **low voltage line** (240 V, 3-phase) to supply customers in the immediate vicinity of the plant. Because this demand is limited, a transformer is used to step up the voltage to 3 kV, for transmission via **two 3 kV lines** to a group of customers about 1.25 km away.

Several of the sixteen main customers are 'generators' – people who were previously running diesel generators and selling the electricity to their own customers. The 'generators' continue their existing business, but they sell on electricity from SRE rather than running their own diesel generators.

The gasification plant also runs **irrigation pumps** connected to the transmission lines and a pipe to supply to farms close to the plant.

6.3.1.4 Economics

The plant cost about **US$ 170,000** (Rs 8.3 million) to construct, about **90% for the gasifier and generation plant**, and **10% for the first 3 kV distribution line**.

The electricity supplied to each customer from the gasifier plant is metered, and customers are supposed to pay each day. Contracts are negotiated with individual customers, at around **US$ 0.15** (Rs 7.5) **per kWh**. As extra customers are connected and more of the available plant capacity is used, the price may decrease.

Customers are charged about **US$0.15/kWh** for electricity, compared with about US$0.28 kWh for diesel generators and US$0.12/kWh for (unreliable) grid supply.

The Capital cost are expected to be recovered in about six years through electricity sales.

6.3.1.5 Operation and feedback

The plant is **maintained by technicians trained** in Bangalore, with **heavy maintenance undertaken by an engineering company** based in Haryana. Both the gasifier and the engine used by SRE have been reliable, and the electricity generated has a stable voltage and frequency, which is particularly important for some of the small industrial users. The plant operates for about 85% of the time during scheduled hours of supply, but down time can usually be arranged for quiet periods so the availability for most users is higher. During the first two years of operation, the plant had to be shut down for only two days for emergency maintenance. With proper maintenance the **plant life should be 15 years**.

Community Energy Cooperative, Battambang - Cambodia

6.3.1.6 Project background

The main objective of this project led by SME (Small and Medium Enterprise, Local Cambodian NGO)) was to support rural economic development and improve competitiveness of rural businesses by setting up a high quality, low cost, member owned electricity service dependent on locally available biomass sources.
The pilot project in Battambang started in 2005. The first 7kW second hand gasifier was replaced by a new one in 2007.

6.3.1.7 Technology

<u>Biomass</u>

Supply

The two local biomass used in the projects are wood (Leucaena) and corn cobs. For Leucaena production, a tree nursery was set up with an area of 300 square meters associated with a 10ha plantation.

Preparation and storage

The Leucaena is chopped into pieces 25 mm long.

The biomass (wood and corn cobs) is stored under cover near the building housing the gasifier.

Gasifier

SME chose a **down draft gasifier** from Ankur Scientific Energy Technologies Pvt. Ltd (India) of **20 kWe** of installed capacity.

The system consume has a specific consumption about **1.5 kg/kWh**.

Syngas cleaning

The cleaning system consists of four filters, a coarse filter of rice husk attached straightly to the reactor through drain box, while two other active filters of sawdust link to this coarse filter and then these two connect to the last one, a safety cotton filter before the purified gas goes into the generator.

6.3.1.8 Customers

80 households from the pilot project and 160 newly connected households are connected to the service through a **low voltage distribution grid** (3 phase - 400V) in a span of 1 km. The consumption are monitored with individual meters.
Alimentation of 20 streetlights was included in the project.

6.3.1.9 Economics

The total capital costs of the project was US$ 76,600 including US$42,000 from UNDP-GEF.

Every household is charged a one-time connection fee of US$17.50. The fee covers all connection expenses from the local grid to the house, including in-house electricity wiring. Once connected, the households pay a tariff based on the electricity consumed and recorded by a meter. The **current tariff is about US$ 0.37/kWh**.

The project operates **without any operating subsidies**: the collected revenues should cover all system operation and maintenance expenditures.

6.3.1.10 Operation and feedback

During the initial pilot, there were technical problems with a second-hand gasifier. By replacing the 7kW second-hand gasifier with a new 20 kW one, some problems with the gasification process were immediately resolved. In its second phase, the CEC still faced some occasional technical challenges. Despite training provided to the CEC, problems in transmission and distribution remain, such as those associated with poor wiring and insufficient poles to support the distribution system.
Technical problems seem to prevail in almost all community-based energy projects, which require a certain level of technical knowledge. Technical training can be provided for instance from both gasifier and the generator contractors through legal agreements at the time of purchase. Agreements should include training and provisions for maintenance services for a given period once the construction is completed.

Source : http://content.undp.org/go/cms-service/stream/asset/?asset_id=2095739

Atmosfair - Lanka Gasifiers, Sri Lanka

6.3.1.11 Project background

A quarter of the households in Sri Lanka have yet to be connected to the electricity grid. Such households generally use either kerosene or diesel generators for lighting needs. The German NGO Atmosfair has developed a rural electrification program in partnership with Lanka Gasifiers through the dissemination of wood gasifiers systems in rural villages.
The project started in 2007.

6.3.1.12 Technology

Biomass

The main used fuel is dry chopped wood.

Gasifier

The systems installed are **12 kWe down draft gasifiers** developed by Lanka Gasifiers.

Syngas cleaning

The syngas cleaning process is composed of three **cyclones** in series collecting soot (carbon black) and some condensation initially associated with a wet cleaning process.
In 2009 the wet gas cleaning was changed for an easy-to-operate **dry cleaning system** (primary and secondary refillable coir fibrechamber).

Generator

The engine used is two cylinder engine specifically designed for producer gas by Lanka Gasifiers.

6.3.1.13 Customers

In each village, about 40 to 70 households are supplied with electricity. **Every household receives 75 – 150 W of electricity for up to 12 hours a day**; thus, there is enough electricity for lightning, radio/television and refrigeration of food items or for the operation of machines in small enterprises.

6.3.1.14 Economics

The families pay a monthly fee of EUR 1.25 and contribute 60 kg of dry chopped wood as fuel. But this is just enough to cover the running costs. The initial investment costs were covered by the project developer. Although the power plant's capacity would allow more families to connect, **most families are unwilling or unable to pay the initial connection fee** of about EUR 30 requested as compensation for the initial contributions of the pioneering families.

All this indicates that **commercial operation of such a plant would not be possible in the given environment**.

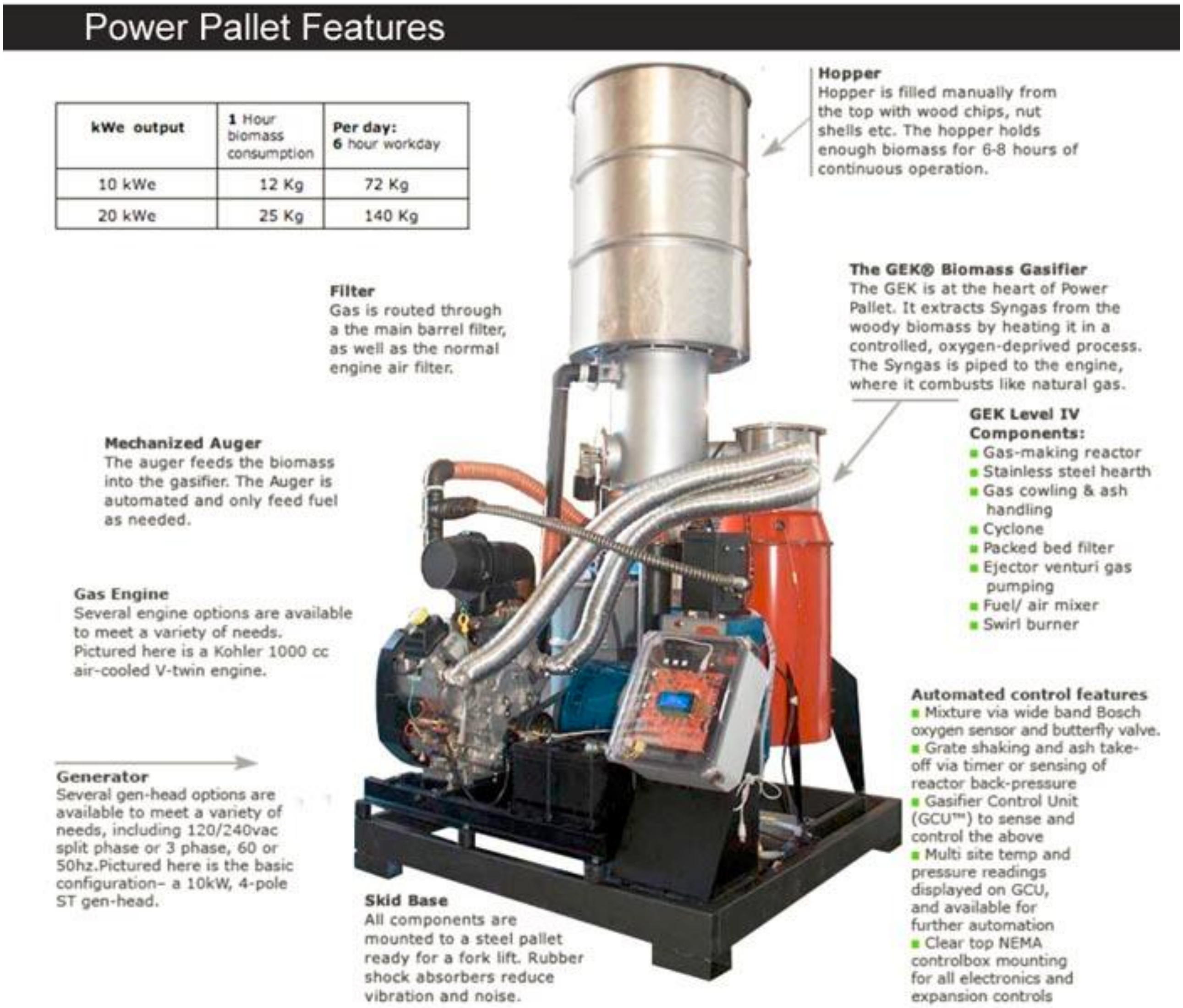
Furthermore, **compared to other renewable energy technologies gasification proved to be expensive**. The per capita investment costs for the gasification power plant were about **30-40% higher** than those for a micro-hydro power plant or solar home systems installed in the region. Obviously the running costs are considerably higher as well.

6.3.1.15 Operation and feedback

At the beginning of the project, **the installation of the machinery took a long time and required a great deal of know-how**. The **operation** of the plant is **laborious** and requires a committed, permanently employed operator. Every day the filters had to be cleaned and once a month the whole plant had to be disassembled and cleaned of tar and soot.

It took more than one year of intense modification and adaptation to get the tar and soot problem under control. Due to the wet gas cleaning system the project had a number of problems in the beginning with high quantities of condensates and liquid waste. A dry gas cleaning system solved this problem and by 2009 the gasifier had been working well for more than one year. However, **the local population can hardly pay the running costs** and it would be impossible to finance the investment costs by the revenues from electricity sales.

Appendix 2 : GEK Power Pallet presentation



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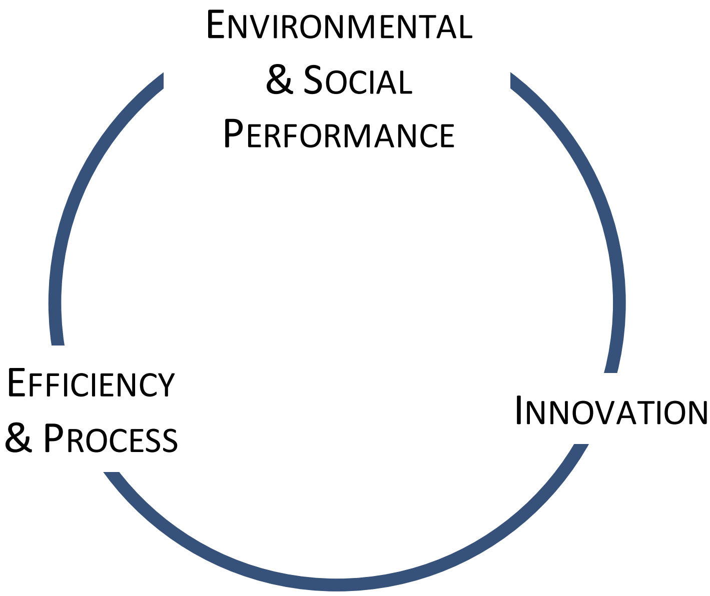

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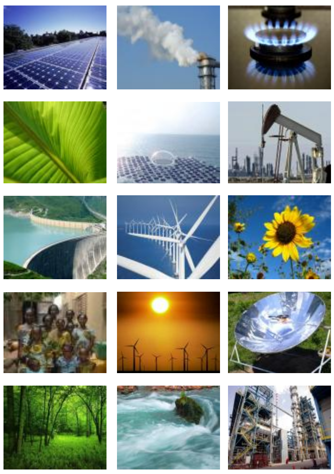

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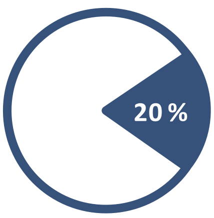

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