De-bushing Project:
Towards a cleaner charcoal production process

Mission Report
Produced for the Namibian Charcoal Association (NCA)

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1 Introduction

The aims and objectives of the assignment are summarised as follows:

♪ To establish a modernised approach to charcoal production that minimises negative environmental impacts as deforestation, smoke fire hazards and excessive environmental harmful waste
♪ To upgrade technical skills & production knowledge among charcoal producers
♪ To increase the productivity and profitability of the charcoal production process
♪ To improve provisions for health and safety of workers involved in the charcoal sector

Furthermore, during this mission, the prices of fossil fuels (diesel, gasoline, gas, electricity) and the prices of wood fuel (firewood and charcoal) were identified. These prices were then compared on a price per kWh basis.

Three rate groups can be differentiated:

♪ Fossil fuels with prices ranging from $1 N / kWh (liquid fuels) to 1.5 N $ / kWh (gas & electricity small power). It must be highlighted that electricity sold to large consumers is more expensive and the price exceeds $2.5 N / kWh
♪ Wood fuel sold directly to users
♪ Charcoal at different stages of the production chain (N $ 0.1 / kWh bulk price paid to charcoal makers, 0.36 N $ / kWh paid to charcoal producers for the 60+ quality, see 3.4.7)

Overall, as is often the case, the price of energy from charcoal is much lower than that of other energy sources. Prices survey is not comprehensive but based on single sampling along the road. For example, prices for liquid fuels listed here are based on the ones charged by a single pump in Otjiwarongo. Only three electricity rates were considered while there are more. These data are illustrated in Figure 1

![The price of Energy in Namibia](figure1.png)

*Figure 1: Energy prices in Namibia, including charcoal (Dom=domestic, Bns=Business, Bns L = Business large)*
2 Charcoal production state of the art

2.1 Main charcoal production phases

While it is possible to carbonize green wood, it is useful to perform a pre-drying. This can be achieved by simply storing the wood in ambient air condition. It will lower wood moisture content to an equilibrium depending on the conditions of temperature and relative humidity of the air in the storage area. Moisture on a wet basis of 25 to 30% (Hbh) is considered acceptable to begin a carbonization cycle. Further drying will benefit carbonization and will result in improved performance. However, in practice this is possible only when an external heat source is available, for industrial carbonization systems or when atmospheric conditions are favourable for drying (hot & dry air) as is often the case in drylands.

Without going into the theoretical details of the slow pyrolysis, carbonization can be defined as the degradation of three wood components: cellulose, hemicellulose and lignin. This transformation takes place in three main phases: drying, proper carbonization and cooling [1].

During drying, the water contained in the wood must be evaporated before the wood components’ pyrolysis can start, even if a pre-drying was carried out. During this phase, the temperature of the wood is about 100 °C. Evaporation of water requires a large amount of energy. In case of “partly combusted wood load systems” this energy is taken from the wood load itself and for other systems, an external energy source may be used. Thus, the more the wood has been dried before carbonization, the better its performance.

When bone dry, the wood temperature still must be increased to 280 °C. The energy required for this step also comes from the combustion of a portion of the wood load (or an external source); it is still an endothermic reaction.

When the wood is bone dry and heated to 280 °C, it begins to decompose spontaneously to form charcoal, and several other components - water vapor, tars and non-condensable gases. Wood carbonization above 280 °C is exothermic. This process continues until it remains only the carbonized residue that is charcoal. If there is no new external heat supply the process stops and the temperature reaches a maximum of about 400 °C. This charcoal, however, still contains significant amounts of tar residues. If the heating is continued, the pure carbon content increases due to the removal and decomposition of a greater proportion of tars.

After carbonization, the load is sealed hermetically to avoid any contact with oxygen of the outside air. The charcoal slowly cools to ambient temperature by radiation.

The quality assessment of charcoal production is a combination of process yield and charcoal product quality. Beside the wood load moisture content, the charcoal production process is influenced by the following parameters:

- Temperature

This is the most important factor; temperature determines the carbonization yield and the physicochemical properties of produced charcoal. The charcoal quality increases with temperature to the detriment of mass yield. Indeed, the higher the carbonization temperature, the more volatiles escape from the fuel, the more its mass decreases and its fixed carbon content increases. A low carbonization temperature leads to a higher mass yield, but also to a charcoal of lower quality. A good quality charcoal should have a fixed carbon content of about 75%, which requires a final carbonization temperature of about 500 °C [1].
**Charring speed**

- During a charcoal production process (slow pyrolysis), the compounds have time to form and react together during side reactions. This is not the case during fast treatments (flash pyrolysis). During flash processes, the contact time and the temperature rise is of about one second. In this case, the main product is not charcoal anymore, but gases and liquids. This does not occur during traditional charcoal production processes.

**Raw material**

- Dense wood gives a dense charcoal and light wood gives charcoal of low density. [2]

- In principle, all wood species can be carbonized to produce a usable charcoal; though dense charcoal (produced from dense wood species) is generally preferred. This is mainly because charcoal is often sold on a volume basis: an empty tin can (though often called "kilo") and bags (called "50 kilos" or “100 kg” bags) are common units for marketing reference. Under these conditions, the denser the wood (and charcoal), the more energy the customer receives for the volume he buys.

- The wood ash content is usually low and has only few variations. The carbonization increases the ash content, but it remains acceptable for its uses. However, the bark contains more mineral material and leads to a lower quality charcoal. The final charcoal ash content may also be affected by dirt, especially in the case of mound kiln processes, in which the product is in direct contact with the ground.

- As noted here above, wood moisture is very important in charcoal production processes. The higher the wood moisture content, the lower the mass yield, as wood drying consumes energy.

- Wood with a high lignin content gives a higher mass yield, mature and healthy wood is therefore preferred for charcoal production.

**Charcoal maker skills**

- For “partly combusted wood load processes”, the qualification of the charcoal maker is crucial. Indeed, the skill to appraise (e.g. smoke colour, smell or intensity) and handle air supply can be acquired only through long practice.

- The impact of this factor is not as important for improved carbonization techniques, but training in their use remains necessary.

**Weather Influence**

- Rain can severely alter the carbonization process, especially for mound kilns and pits; it significantly increases the process duration.

- Heavy rain before ignition leads to wood load moisture absorption.

- A strong wind induces a fast carbonization of the side that is exposed and leads to increased fire risk.
2.2 General rules for an effective and efficient carbonization

Sanogo et al [1], reviewed the most important steps to complete a ‘good’ mound kiln carbonisation. These rules also apply to metal and brick kilns and are listed below.

♪ Wood piling and arrangement should be made in a way that facilitates air penetration in the feed and makes it and more uniform, to prevent uneven carbonization;
♪ The wood log size must be relatively uniform, except brushwood for ignition and wood used to fill the voids;
♪ No wood species mixture;
♪ The carbonization furnace must be as airtight as possible, except for the vents;
♪ The logs of bigger diameter are placed in the centre of the load, as these areas remain hot longer;
♪ The carbonization time increases with the size of the wood logs;
♪ The carbonization spot: the site shall be flat, not wet or soggy (if the soil is very moist, wood burning energy would also be used to dry the spot). It shall be close to the wood harvesting area, clear and out of vegetation. It shall allow easy handling when loading / unloading wood and charcoal. Moreover, it shall be free of stones and especially trees stumps .
♪ A grid may be formed by placing beams at the base of the system, they are composed of 10-20 cm diameter healthy wood logs. Their main role is to ease the air and gas flow inside the kiln.
♪ The load may be vertical (a wood floor is previously arranged on the grid, then the wood logs are arranged vertically in layers), horizontal (in radius or crown) or bulk (especially in the case of small dimensions’ wood logs).
♪ For ignition and wood load preheating, the use of small wood pieces, twigs or embers is preferred, they are placed at the centre of the ignition point. Fire development is facilitated by creating a "chimney effect" (openings / vents are created at the base and at the top of the furnace). Thus, the fire grows rapidly in the wood load. Consequently, the water contained in the wood is vaporized and escapes as white smoke. The air inlets are then (partially) closed and the wood load continues to dry. The duration of this phase depends on the initial wood moisture. When the fire is powerful enough, carbonization begins Air access is then reduced again and any air input or outlet other than those dedicated to this purpose, are blocked. The carbonization zone expands. During this phase the smoke becomes yellowish, dense and has a slightly pungent smell. The charcoal maker needs to ensure that the expansion is uniform across the load. To do so, he modulates the air inlets to foster air flow to the cooler areas and reduce it in too hot areas. The initial hours of carbonization process are crucial for its outcome.
♪ When the charring zone is well developed, the air inlets and flue gas outlets are reduced. The objective is to maintain a temperature above the exothermic phase.
♪ Extinction: when carbonization is complete, the colour of flue gases changes and becomes blue and transparent. All inlets and outlets are then sealed and all openings that could let in air are clogged.
♪ The wood load cooling phase starts. Its duration depends on the type of furnace and load (volume, mass & density).
♪ When the kiln has cooled down, the charcoal can be removed from the kiln and packaged. Caution is recommended, as the freshly charred charcoal might oxidize upon its exposure to the air. This oxidation can raise the charcoal temperature to a level high enough to start its spontaneous combustion. Consequently, a cooling-off period is recommended before packaging.
2.3 Charcoal: Quality & yields

Different yield calculation methods are proposed in the literature: Mass yield, Commercial yield, Weighted mass yield, Technological yield and Energy yield [1] [3] [4] [5]. Combined yields have also been described [6] as well as the reference mass yield [7] [8]. In the present report, the following formulas were applied:

The moisture content of solid biofuels is a percentage of the wet weight

\[ H_{bh} = \frac{M_H - M_A}{M_H} \times 100 \]

- \( H_{bh} \): Wet based Moisture Content (%)
- \( M_H \): Wet mass (g)
- \( M_A \): Dry mass after drying to constant mass (anhydrous) (g)

Evaluations conducted as part of this study will be limited to the use of the mass yield (anhydrous basis) as defined in [6]. The mass of unburnt logs is deducted, from the mass of charcoal as well as from the initial mass of the wood load. To compare data from different carbonization processes, the mass yield must always be calculated on an anhydrous basis.

In case of retort kilns and kilns which require wood fuel in their process, the wood fuel shall be included in the initial wood mass \( M_{ba} \). Nevertheless, for productivity evaluation purposes, it is sometimes interesting to determine the yield without considering the wood fuel, the yield is then calculated by considering the wood load mass from which the wood fuel mass is subtracted (\( M_{ba} - \) Wood fuel mass). The mass yield considering the wood fuel mass is sometimes referred as “global yield” and the yield which does not consider this mass is simply referred as “yield without fuel”.

\[ RM_{ba} = \frac{M_{ca}}{M_{ba}} \times 100 \]

- \( RM_{ba} \): Mass yield on anhydrous basis (%)
- \( M_{ca} \): Charcoal mass - anhydrous (kg)
- \( M_{ba} \): Wood mass – anhydrous (kg)

Although this yield is not used later in the paper, the (higher) energy yield is presented below. This yield is always greater than the mass yield. Indeed, it considers the energy contained in charcoal products and refers to the energy that is contained the initial load. As the calorific value of charcoal is higher than that of wood, the energy yield is higher than the mass yield.

\[ RE' = \frac{M_{ca} PCS_{ca}}{M_{ba} PCS_{ba}} \times 100 \]

- \( RE' \): (Higher) Energy yield - (%) 
- \( M_{ca} \): Charcoal mass - anhydrous (kg) 
- \( M_{ba} \): Wood mass – anhydrous (kg) 
- \( PCS_{ca} \): Charcoal Gross Calorific value (MJ/kg) – about 20 MJ/kg 
- \( PCS_{ba} \): Woodl Gross Calorific value (MJ/kg) – about 33 MJ/kg 

2.4 Charcoal production processes

2.4.1 Two main charcoal production processes

Carbonization techniques are conventionally grouped into “partly combusted wood load processes”, and (industrial) retorts [7]. These two charcoal production principles are illustrated by Picture 1 & Picture 2.

The “partly combusted wood load processes” may be further subdivided in two groups depending if airflow is generated directly or indirectly. [1] The yields of these alternatives as found in the
Different mound kilns techniques are compared in Schenkel et al., 1997 [6]. This review is based on an analysis of more than 20 scientific papers and concludes that mound kiln techniques, if properly conducted, achieve yields like those obtained with improved techniques (i.e. metal kilns or brick kilns).

Retort kilns allow for combustion of gases generated by the carbonization. These gases can be used to supply heat to the kiln itself, or a kiln nearby.

2.4.2 Partly combusted wood load processes

2.4.2.1 Mound Kilns

Conventionally, there are three types of mound kilns: traditional mound kilns, horizontal mound kilns and improved mound kilns, represented mainly by the Casamance mound kiln in North-West Africa and the MATI mound kiln in Madagascar.

The traditional vertical mound kiln has a circular base (Picture 3 & Picture 4). It consists of wood arranged vertically around a central pole and small brushwood arranged in the gaps. The stake or mast is removed, thereby creating at the centre of the wood load a hole for lighting. The cover consists of plant material (straw, grass & branches) topped with a layer of soil (sand or silt if possible). The ignition of the wood load takes place at the centre of the mound kiln by dropping embers in the hole for lighting. After the fire has expanded and moved higher in the hole of lighting, the carbonization front progresses from top to bottom, it has a fan shape. The conduct of these mound kilns requires great skill and almost permanent monitoring.

When carbonization is complete, the mound kiln is covered with an additional layer of soil to the seal it during cooling. The duration of the carbonization is approximately about 50 hours for small kilns (about 10 cubic meters). Cooling can take several days for the biggest kilns.
The horizontal mound kiln (Picture 5 & Picture 6) is very similar to the traditional mound kiln regarding coverage and the modus operandi. Its shape is like a half cylinder or a flattened rectangle. The two significant differences from the previous technique are as follows:

♫ Wood is piled horizontally (longitudinally).
♫ The carbonization front moves from one end to the other.

In the case of horizontal mound kilns, the wood load is placed transversely over a series of logs placed from end to end. They constitute an airflow grid. Sometimes the logs of the wood load are arranged longitudinally. Again, brushwood is used to fill the gaps between the logs. Lightning is done on the leeward side of the kiln. In the case of large-sized mound kilns, charcoal may be collected at ignition side before the carbonization of the entire kiln is completed. Horizontal kiln volumes can reach up to 100 cubic meters, the complete cycle of carbonization may take more than 3 weeks.

Improved mound kilns (Picture 7 & Picture 8) have been developed to improve, accelerate and facilitate the monitoring and the conduction of the charcoal production process. Among the improved mound kilns, the Casamance kiln is probably the most widespread.

The installation of this mound kiln requires good air circulation (floor vents and base composed of small logs, vents are formed by using pipes at the base of the kiln). The wood is piled according to size (small branches at the periphery and large logs at the centre of the kiln). The coverage is the same as for traditional kilns.

The main improvement is the use of a chimney made of inexpensive materials (old 200 l drums). The chimney allows a faster carbonization process, and facilitates the control of the gas flow direction. In addition, the yield is improved through the downdraft. A mound kiln of 100 cubic meters requires 3 days carbonization and 4 days cooling.
The mound kilns have the advantage of being mobile, and require relatively little investment because they can be built from local materials. Furthermore, their capacity is adjustable to the needs of the charcoal producer and to the available raw material. On the other hand, mound kiln efficiency is highly dependent on charcoal maker skills, the process requires a heavy and permanent workload. Moreover, the production quality and the yields obtained are very variable, from 12 to 25%. Indeed, without ongoing monitoring, the risk of burning off – leading to almost complete destruction of the wood load - is high. The above-cited carbonization processes generate emissions typical of incomplete combustion, including CH₄, which is of particular relevance for the greenhouse effect.

2.4.2.2 Metal Kilns

A cylindrical metal kiln was optimized by the UK Tropical Products Institute. This work was based on a similar furnace that was used in the UK & Europe since the 30s. This kiln (TPI) was then disseminated in many developing countries. Besides being mobile, metal kilns allow to conduct the charcoal process accurately by using air ducts and metal chimneys that allow efficient control of air access. The observation of smoke escaping from the chimneys makes it possible to identify areas where charring occurs and to control it. It is also possible to direct the incoming air to areas where charring has not yet started. These furnaces generally have a diameter and a height of 2m. They are relatively easy to operate and the production cycle is relatively short (5-6 days) due to a cooling phase accelerated by metal walls. Metal kilns have the advantage of short carbonization cycles which are easy to conduct. Production is more homogeneous, both in terms of charcoal quality and yield regularity. The average yield is about 22% (from 12 to 30%). The risk of fire is reduced. These kilns however have some disadvantages. Notably, they generate a lot of smoke, have a limited life time and require equipment and skills to perform the welds needed to make them. Picture 9 shows a TPI kiln used to make charcoal from sawmill residues in Cameroon.

The capacity of these kilns is fix and cannot be adjusted. Metal kilns have emission characteristics of incomplete combustion, including CH₄, which particularly impacts the greenhouse effect.
2.4.2.3 Brick Kilns

Traditional models of brick kilns have been improved over the centuries, but 3 of them must be highlighted for their widespread use, especially in the Americas: the Brazilian kiln, the hemispherical Argentine kiln, and the Missouri kiln in the United States.

The Missouri kiln was developed in the United States. It is generally made of reinforced concrete or concrete blocks, it has steel doors and a chimney. Its performance is comparable to the Argentine and Brazilian kilns. The large metal doors allow the use of mechanical equipment for loading and unloading. Regarding developing countries, it has two disadvantages: it requires a large amount of steel and cement for its construction, which is expensive and usually need to be imported. Moreover, it cools down more slowly than other ovens. Therefore, its use is more suitable for temperate countries, where the cooler climate allows easier cooling and where the materials and skills needed for concrete and steel building are easier to find.

Argentine and Brazilian hemispherical kilns (see Picture 10 & Picture 11) are completely made of bricks. The brick quality can be moderate (low degree of cooking). The bricks are assembled using clay. These kilns are adjustable in size and sturdy, their lifetime varies from 5 to 8 years and they are relatively easy to operate.

The main drawback of these kilns is that they generate a lot of smoke at ground level, which, in addition to the pollution generated, makes working conditions of charcoal makers very difficult. Brick kilns have the advantage of a limited investment and are easy to operate. Production is more homogeneous than in the case of metal kilns, both in terms of charcoal quality and in terms of yield. An average yield of about 22% (from 12 to 30%) can be expected. The risk of fire is reduced. However, these kilns have a fixed capacity and cannot be adjusted. Their construction requires skilled workers and suitable equipment. The carbonization process generates emission characteristics of incomplete combustion, including CH₄, which particularly impacts the greenhouse effect.

2.4.3 Retort Kilns

2.4.3.1 Industrial Retort kilns

The principle of operation of a vertical cylindrical retort (illustrated by Picture 12) is to use the heat produced by the combustion of the pyrolysis gases to dry and char the wood load. During the starting phase, a fire is lighted at the bottom of the retort. Through the vents at the base (which are completely open), a fire is also lighted in the wood load. Once the fire has started, wood is added through the hopper. Once it ignites, the vents are closed. One of the air inlets (usually one located at the downwind side) is opened, and the hopper is partially closed. Wood feeding is done gradually.
until the cell is full. In operation, the trap at the base of the retort is opened every two or three hours, to fill a metal drum with hot charcoal. Once filled, the barrel is closed and allowed to cool off. A new load of logs is introduced through the hopper after each collection of charcoal, so that the operation of the retort may be continuous.

The principle of retort kilns has experienced many modifications in its implementation, most of which were developed by charcoal producers themselves. Few of the models are commercially available and many of these producers are no longer in business, leading to a loss of knowledge in the implementation of the retort principle. Some names remain: Lambiotte, Martezo, Herreshof. Retorts have evolved in the last decades years, some furnaces have now lower capacities and nevertheless allow the combustion of the pyrolysis gases. This is the case of the Ukrainian retort kiln which has been visited at CCF (Cheetah Conservation Fund – Otjiwarongo) during this mission. This furnace consists of two compartments connected to a burner. Each compartment contains three boxes in which wood logs (or wood briquettes, in case of CCF) are loaded. The boxes are heated through gas combustion of the other compartment. Once carbonization is completed, the sealed boxes are replaced and allowed to cool.

Retort furnaces have the advantage of a continuous process and homogeneous production of high quality charcoal. In addition, due to the combustion of the pyrolysis gases, this principle of charcoal production is much more environmentally friendly (no CH₄ emissions). The observed yields are high (>35%). However, the investment required to implement retorts kilns are very high.

2.4.3.2 Small scale “retort” kilns

2.4.3.2.1 A plethora of prototypes

Many prototypes of small scale retort furnaces have been developed. Human imagination seems boundless in this area. The results of an internet search on the subject illustrates the wide variety of designed models (see Picture 14 to Picture 19). Some names include: Mekko Kiln, Kiln Kohn Tikki, Gallon drum ...

However, few of these alternatives are available on the market and when they are, their cost seems high in relation to their volume. The announced yields are seldom confirmed by independent testing and the wood fuel required for their operation is almost never included in the calculation. Very often, leaking carbonization chambers impose the use of water to cool the charcoal which leads to a lower quality as the product breaks into small pieces).
2.4.3.2.2 Adam Retort kiln

The Adam Retort, named after its inventor, has to be highlighted because it was probably the first brick kiln designed to allow the combustion of methane emitted during the carbonization process. According to the designer, the heat from the methane combustion allows (through a system of canals under the carbonization chamber) to heat the wood load and by that to fulfil the energy needs of the process. However, it turns out that despite the spectacular combustion, the influence of the heat it produces on carbonization performance is marginal. A recent study, however, reported a reduction of 50% CH₄ emissions compared to traditional mound kilns [13]. Construction plans and the user license can be purchased from the inventor of the technology. This type of kiln has been implemented in several countries worldwide.

Several weak points were identified by users:

- Brick walls and junction with metal lids appear to be porous, preventing airtight cooling. This results in losses due to wood load combustion and imposes the use of water to stop the process.
- The pyrolysis gas is not burned completely and without heat recovery.
2.4.3.2.3 Green Mad Retort

The Green Mad Retort (GMDR - Picture 21) was developed in Madagascar, to produce charcoal from Eucalyptus wood harvested in plantations located around Antsiranana, in the North of the island. The GMDR has double walls which ensures its perfect sealing during the cooling phase. Through a thermal gas cleaning system, this brick kiln enables combustion of the methane generated by the pyrolysis. The combustion occurs before methane is released into the atmosphere. Although the heat from this combustion is not yet recovered or used, this system makes GMDR one of the cleanest technologies to produce charcoal: less than 1 kg CH$_4$ is emitted to produce one tonne of charcoal [15]. In comparison, the production of one tonne charcoal in traditional mound kiln generates around 40 kg of CH$_4$ and the production of one tonne of charcoal with the Adam kiln generates 20 kg [13] [14]. Moreover, this carbonization technique leads to high mass yields of about 40%. As shown in Figure 2 & Figure 3, the GMDR consists of 3 parts: an external combustion chamber, where lower quality wood or other biomass may be used, a charcoal chamber and a chimney at the basis of which a simple system allows the post-combustion of the gases generated by the carbonization.

![Picture 21: Green Mad Retort](image1)

![Figure 2: Green Mad Retort - Principle](image2)

![Figure 3: Green Mad Retorts, side views](image3)

2.4.3.2.4 Mindourou Kiln

The Mindourou kiln is also a brick oven. It was developed to produce charcoal from sawmill residues in Eastern Cameroon. Here, the sealing problems have been solved by placing the kiln in a pit. The wood load is placed in the carbonisation chamber and covered by metal lids. Sawmill residues are often large, consequently this oven was sized to allow the use of these wood piece without requiring previous cuttings. The length of a furnace module is 6 meters, at a width of 1.8 m and a depth of 2m. As the GMDR, the Mindourou kiln is equipped with an external combustion chamber. The Mindourou kiln may in the future be equipped with a thermal gas cleaning system like that used on the GMDR. In addition, Mindourou kilns are designed to use the heat generated by the combustion of one module to supply the combustion chamber of the next one. This concept, which remains to be implemented, is shown in Figure 4. Although it is still in development, the Mindourou furnace already reaches high mass yields of around 40%. The charcoal product is also of very good quality.
2.4.4 Summary

The analysis of Table 1 shows the very high variability of carbonization mass yields in the literature, regardless of the technique used. Factors that influence the carbonization have been described above (§2.2). According to [6], the following yields are generally obtained: mound kilns: 20 to 30%, brick kilns: 25%, metal kilns 25%. The mass yields that can be obtained by using retort kilns are slightly higher, of the order of 30% [8].

Besides the yield (mass or energy) and its strong implications on pollutant emissions, carbonization time must also be considered. The time required for a cycle has consequences at the logistic and organizational level of the site. For mound kilns, cycles time needs can vary from 4 to 45 days. Here, the Casamance kiln shows an advantage over the traditional mound kilns, the first showing a much shorter carbonization cycle (9 to 14 days as against 43 to 45 days depending on the volume of the load).

New developments in "retort" kilns, small, built of brick, allow the production of charcoal at high mass yields and the elimination of methane before its release into the atmosphere. The Green Mad Retort emits less than 1 kg methane to produce one tonne of charcoal, the yield is around 40%. Similar yields were obtained with the Mindourou kiln.
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<td><strong>Partly combusted wood load processes</strong></td>
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<tr>
<td><strong>Mound Kilns</strong></td>
<td>♦ Mobile (off road) ♦ No wood log displacement ♦ Local Materials ♦ No Investment ♦ No splitting needs ♦ Adjustable Capacity ♦ Use of biomass residues</td>
<td>♦ Demanding regarding operator skills ♦ Requires a lot of manpower (permanent) ♦ Sensitive to climatic variations ♦ Coal of varying quality and soils contamination by the cover ♦ Low energy efficiency ♦ Significant pollution</td>
<td>Traditional 12 to 34 26 15-30 Improved 19-42 27</td>
<td>[6] [5] [1]</td>
</tr>
<tr>
<td><strong>Pits</strong></td>
<td>♦ Mobility ♦ Skidding on small areas ♦ Local materials ♦ Very low to zero investment ♦ Charcoal production from large wood logs possible, without slitting ♦ Adjustable capacity ♦ Use of biomass residues</td>
<td>♦ Demanding regarding operator skills ♦ Requires a lot of manpower (permanent) ♦ Sensitive to climatic variations ♦ Requires a deep and cohesive soil ♦ Low energy efficiency ♦ Significant pollution</td>
<td>Subri 22 – 36 30</td>
<td>[6] [8]</td>
</tr>
<tr>
<td>Kiln Type</td>
<td>优点</td>
<td>缺点</td>
<td>型号</td>
<td>价格</td>
</tr>
<tr>
<td>----------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-------</td>
</tr>
<tr>
<td>Metal Kilns</td>
<td>sgiving needs for large timber</td>
<td>易操作</td>
<td>Mark V</td>
<td>12-32</td>
</tr>
<tr>
<td></td>
<td>Homogeneous and clean coal</td>
<td></td>
<td>Magnien</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Short cycle by rapid cooling</td>
<td></td>
<td>Not mentioned</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>Retort Kiln</td>
<td>Controlled and constant quality</td>
<td>Low pollution to zero</td>
<td>Medium investment</td>
<td>23-32</td>
</tr>
<tr>
<td></td>
<td>High mass yield</td>
<td></td>
<td>Average technicality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High energy efficiency</td>
<td></td>
<td>Fixed installation</td>
<td></td>
</tr>
<tr>
<td>Continuous</td>
<td>Controlled and constant quality</td>
<td>Low pollution to zero</td>
<td>Considerable investment</td>
<td>26-35</td>
</tr>
<tr>
<td>processes –</td>
<td>High mass yield</td>
<td></td>
<td>High-tech</td>
<td></td>
</tr>
<tr>
<td>industrial</td>
<td>High energy efficiency</td>
<td></td>
<td>Expanded area of supply</td>
<td></td>
</tr>
<tr>
<td>retorts</td>
<td>Low pollution to zero</td>
<td></td>
<td>Wood transport</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Automatization</td>
<td></td>
<td>Splitting and wood preparation</td>
<td></td>
</tr>
<tr>
<td>Mindourou Kiln</td>
<td>Controlled and constant quality</td>
<td>Low pollution to zero</td>
<td>Medium investment</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>High mass yield</td>
<td></td>
<td>Average technicality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High energy efficiency</td>
<td></td>
<td>Fixed installation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low pollution to zero</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GMDR</td>
<td>Controlled and constant quality</td>
<td>Low pollution to zero</td>
<td>Medium investment</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>High mass yield</td>
<td></td>
<td>Average technicality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High energy efficiency</td>
<td></td>
<td>Fixed Installation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low pollution to zero</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.5 Pollution associated with charcoal production

After a life-cycle assessment of different charcoal supply chains of the Brazilian steel industry, it appears that among the fuel production steps, the carbonization has the heaviest environmental impact. Nevertheless, replacing the traditional brick kiln by an industrial retort kiln provides a significant reduction of the environmental impact of carbonization [10]. These results confirm previous studies, although they are few [7]. The emissions to be considered during the carbonization process are: the non-condensable gases (CO<sub>2</sub>, CO, CH<sub>4</sub>, H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>), the condensable gases and / or their condensates and fine particles. The proportions in which these gases are emitted depend mainly on the carbonization temperature (indication: CO<sub>2</sub>: 32 to 36%, CO: 29-55% CH<sub>4</sub>: up to 15%, but in small scale production, the value of 2, 5% may be admitted).

Table 2 compares the emission (per tonne of charcoal) generated by two different carbonization processes: the first one is a partly combusted wood load process, the second is a retort type kiln and allows complete combustion of the carbonisation gases.

<table>
<thead>
<tr>
<th></th>
<th>Partly combusted wood load kiln</th>
<th>Industrial Retort Kiln</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust</td>
<td>32</td>
<td>3</td>
</tr>
<tr>
<td>CO</td>
<td>340</td>
<td>12</td>
</tr>
<tr>
<td>VOC (excl. methane)</td>
<td>100</td>
<td>9,5</td>
</tr>
<tr>
<td>HCT (excl. methane)</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Methane</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Phenols</td>
<td>0,6</td>
<td>0,2</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>48</td>
<td>4,5</td>
</tr>
<tr>
<td>Methanol</td>
<td>8</td>
<td>0,75</td>
</tr>
<tr>
<td>Formic acid</td>
<td>10</td>
<td>0,85</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>4</td>
<td>0,15</td>
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<tr>
<td>Furfural</td>
<td>5</td>
<td>0,5</td>
</tr>
<tr>
<td>HAP</td>
<td>1,35</td>
<td>0</td>
</tr>
</tbody>
</table>


The environmental impact of carbonization gas is threefold: indeed, a gas such as CO is toxic and therefore has a direct effect on human health. Acid emissions (acetic, formic, propionic ...) and polycyclic aromatic hydrocarbons have environmental effects at the local scale (e.g. acid deposition). Picture 25 to Picture 28 illustrate the impact of smoke on a local scale and on the working conditions of charcoal makers. Gases such as CO<sub>2</sub> and CH<sub>4</sub> are known for their impact on the greenhouse effect. CH<sub>4</sub> has an impact on the greenhouse effect 21 times that of CO<sub>2</sub> [11].

Picture 25: Smoke emission due to charcoal production (1)  Picture 26: Smoke emission due to charcoal production (2)
In a first approach, GHG emissions will be estimated on a mass yield basis. The method of calculating carbon emissions is mainly based on the method presented by Girard in [4]. This method estimates the minimum potential reduction in carbon emissions (tonnes of CO\textsubscript{2} equivalent - T CO\textsubscript{2} eq) through enhanced performance of the used carbonization kiln. It considers as a reference a carbonization technique having a mass yield (RMBA) of 12%. This yield, very low but plausible, is the lowest yield observed by [6] and from the reviewed literature. It will be compared to different methods of carbonization for which yields are presented in Table 1. The results of this analysis are presented in Table 3. The evolution of the quantity of T CO\textsubscript{2} eq avoided by improving carbonization yield is also illustrated in Figure 5.

The results presented in the upper part of Table 3 and in Figure 5 clearly show the environmental benefits of using improved carbonization techniques. Thus, compared to a low yield carbonization, the use of a partly combusted wood load process (brick or metal) having a mass yield of 25% will avoid the emission of at least 7,94 tonnes T CO\textsubscript{2} eq per produced tonne of charcoal. It would be between 10,4 & 10,7 tonnes for industrial carbonization system (38% mass yield). CO\textsubscript{2} Carbon conversion factor is 3.66.
The calculation method, however, is only based on the mass yield and does not consider the quality of the emitted gases. Carbon is emitted in several forms, but for simplification only CO\textsubscript{2} and CH\textsubscript{4} will be considered here. CO\textsubscript{2} is emitted by all the considered carbonization techniques, whereas CH\textsubscript{4} is emitted only by the partly combusted wood load processes. Indeed, the retort techniques emit no or only very little CH\textsubscript{4}. The results shown in the lower part of Table 2 and Figure 5 clearly demonstrate the environmental benefits of burning CH\textsubscript{4}. Thus, considering the impact of CH\textsubscript{4} and compared to a low carbonization yield (12%), using a partly combusted wood load process (brick or metal - 25% yield) avoids the emission of 11,91 tonnes of CO\textsubscript{2} equivalent per tonne of charcoal produced. It would be between 16,6 and 16,9 tonnes for a carbonization system transforming CO\textsubscript{2} into CH\textsubscript{4}. CH\textsubscript{4} carbon conversion factor is 76,9.
3 The situation in Namibia

3.1 General context: bush encroachment

The areas concerned by bush encroachment in Namibia (see Picture 29) cover about 300 000 km² [16]. Bush species compete with herbaceous vegetation that constitutes the feed of livestock on such surfaces (see Picture 30). This competition is such, especially during drought periods, that the farms’ productivity has fallen drastically in recent years. The elimination of this vegetation to facilitate regrowth of the grass is the main reason for the de-bushing operations conducted by farmers. Until the recent partial ban of the practice, the elimination of the bush using herbicides was still widespread.

For farmers, the production of charcoal is primarily a way to reduce costs related to the elimination of bushes. Unlike chemical removal, mechanical operation requires monitoring because regrowth - although appreciated by game and livestock - is often denser than was the original bush. On the other hand, it seems that the branches left after harvesting facilitate regrowth of grass (protection against the sun, against livestock, surface runoff mitigation by water retention).

Aboveground biomass per hectare of the bush vegetation has been estimated at 30 tonnes of dry matter, from which 10 tonnes can be harvested sustainably [16]. The species in the bush are characterized by a high wood particle density (an average of 770 kg / m³ will be considered later in this document) and a high ash content. Weather conditions in Namibia (usually high temperature and very low relative air humidity), are favourable for wood drying. Wood can reach humidity values lower than 15%. However, it was observed that generally the wood undergoes only a very short drying period (several days maximum) between cutting and carbonization.
3.2 Charcoal value chain

The charcoal value chain is well organized in Namibia. The owner of a farm generally operates independently or delegates to a manager. He recruits charcoal makers, buys their production, and transports it to a place accessible to processors’ trucks. Processors buy and transport the charcoal to their sieving and sorting plants where charcoal is sorted and divided into quality classes before being, for the most part, exported.

3.2.1 Producers

The farmer hires charcoal makers and facilitates the production of charcoal by providing the carbonization kilns. He also organizes the harvesting operation, sometimes providing machines to mechanize a part of the harvesting (See Picture 32). However, it should be highlighted that charcoal production is not widespread. Many farmers burn the wood on site after cutting in order to promote regrowth of grass (Picture 33). For charcoal production, the area of the farm is generally divided into "camps", i.e. areas that will be fully harvested before moving to the next one. The cutting planning of some farms could be improved, as without instructions to charcoal makers the trees are usually harvested in a rather unorganised way. For organization and control purposes, some operators have established transects systems which also facilitate the collection of charcoal and reduce the risk of fire (Picture 33 to Picture 37). It has to be highlighted that some tree species are protected and that trees having a diameter over 18 cm cannot be cut.

Charcoal makers are responsible for the tree cutting and felling, they also produce the charcoal and pack it in bags. The farmer buys the charcoal bags after weighing. The price is currently at 750 N$ per tonne of charcoal. A harvesting productivity test was conducted during this mission (Picture 31). Based on the amount of wood cut by two men within two hours, it can be estimated that an experienced charcoal maker may cut 150 kg of wood reported in the anhydrous mass within one hour.

The charcoal is then transported to the collection point (Picture 39 & Picture 40) to be transported to a calibration plant that buys it for N$ 1500/tonne in bulk. Several producers have started the process to obtain the FSC label (Picture 38). In this case, evidence must be presented that the bush is managed sustainably, which is sometimes contradictory to the goal of reducing the bush and replacing it by grass. However, according to some producers, it seems possible to ensure sustainable production of charcoal while increasing agricultural productivity of the farm. In addition to a sustainable management, efforts must also be undertaken in the field of training and welfare of charcoal makers.
Picture 34: Harvesting transect in a camp (year 2)

Picture 35: Harvesting transect (year 1)

Picture 36: Harvesting transect identification (& numbering)

Picture 37: Harvesting transect, the wood is moved to the place where it will be transformed in charcoal

Picture 38: FSC charcoal

Picture 39: Charcoal stock at production site

Picture 40: Charcoal stock at production site, along the road to be loaded on trucks

ECO- De-bushing Project: Towards a cleaner charcoal production process, Namibia, October 2016
3.2.2 Processors

The charcoal is transported from the production site to a sorting plant. Namibia has a dozen of such processors who basically all operate in a similar way (Picture 41 to Picture 48). After receiving the charcoal bags (and sometime having taken a sample for quality analysis – e.g. moisture), the bags are dumped into the hopper of a mechanical screen (rotating or vibrating). This sieve sorts bulk charcoal in different categories having different values. Fractions for export are then bagged according to customer demand (charcoal dimensions, mass bags, logos ...). Finally, they are placed on pallets to be exported.

A note must be made about the working conditions in these factories sorting charcoal. Handling charcoal generates large amounts of dust which is suspended in the air and inhaled by the workers. Masks are usually provided to the staff, but this individual protective equipment should be complemented by vacuum and air filtration systems.
Generally, four fractions are separated by the processors, dimensions may be somewhat different from one operator to another. Figure 6 is based on information gathered from two processors; it illustrates the average charcoal particle size distribution. These fractions have different destinations and different prices. To recap, the charcoal is typically purchased at N$ 1,500 in bulk. The fraction "Sand & Ash" has no use (if it is a field application to improve soil fertility), it has thus no value either. The fraction "5 to 20 mm" is intended to produce briquettes or to be exported to South Africa, its price is N$ 750 / tonne. The third fraction "20 to 60 mm" is intended for export to the Northern hemisphere, its price is N$ 1,850 / tonne. The best quality of charcoal consists of the fraction "60 +" also known as "restaurant quality", this fraction has a value of N$ 3,000 / tonne.

### 3.2.3 Briquettes

The "5-20 mm" fraction is exported to South Africa where it is pressed into briquettes, the pressing is sometimes made by the processor himself. Indeed, some processors have the required equipment for briquetting production (Picture 49 to Picture 51). The scale of production depends on the producer. Generally, corn starch is used as binder. The air drying does not always seem to be fast enough, especially in the rainy season, thermal drying alternatives have therefore been tested.
3.3 Kilns

3.3.1 Namibian traditional Kiln

3.3.1.1 Principle

The most used charcoal production technique in Namibia is the metal kiln. This kiln is made of a bottomless metal drum. Even though there are variants (including square barrels), the most common dimensions of this kiln are dictated by the standard dimensions of the 1.6 mm thick metal sheets (3.65m x 1.225m). The sheets are bent along their length and the two ends welded together. The result is a cylindrical drum 1.16 m in diameter and 1.225 m height. A metal plate is welded on the top (easy to see on Picture 52), a rectangular opening is made to introduce the wood load. This opening is sealed with a lid for the cooling step. Drums have a price of N$ 2,000, they are mobile and their use is well known by charcoal makers. The carbonization cycle takes 5 to 6 days.

The operating principle is quite simple, and is illustrated by Picture 52 to Picture 66. Two alternatives were observed to start the process. The first is to light a fire with brushwood at the bottom of the drum. Afterwards the drum is progressively filled by wood until the upper level is reached. The second alternative is to fill the kiln first, then start the fire. The next step is the same in both cases. The air access at the bottom of the kiln is reduced to control the load combustion and to avoid that the fire reaches too high temperatures. Due to combustion, the wood at the bottom of the kiln decreases in volume and strength, consequently the charge collapses. The charcoal makers promote this collapse by exerting pressure on the top of the load. Free space at the top is reloaded with additional wood. The additional wood is in contact with the gases from the combustion which takes place at the base of the load, which favours the temperature increase and drying.

is done after every collapse, about once every hour. The process is complete when the kiln is completely full of embers. Then, air access is blocked and the lid placed on top of the kiln. The tightness of the base is secured by dry soil and sand, while the cover is clogged with mud. The charring phase has a duration of 2 to 3 days, to which must be added 2 to 3 days for cooling. Charcoal may then be taken out the kiln and bagged after a while.

This carbonisation process, despite its many advantages (low cost, wide distribution, high productivity, good knowledge of technology by charcoal makers...) does not have a good image, mainly because the smoke it generates is abundant and disturbing. In addition, the charcoal it produces generally has a medium quality.

3.3.1.2 Namibian traditional kilns main characteristics

♭ Mobile
♭ Cost effective (2,000 N$)
♭ Long lifetime (10 years & more)
♭ Supposed low yield
♭ Generates a lot of smoke
♭ Charcoal contains a high share of sand, ash & small pieces
♭ Unstable production (sometime very good, sometimes very poor charcoal)
♭ After ignition, the kiln is filled up to be full of charcoal (3+3 day process)
♭ Quality & yield seems “dependent on charcoal makers’ skills”
Picture 52: Surface cleaning before kiln placement

Picture 53: Wood is moved on a short distance to the kiln.

Picture 54: For the carbonisation cycle is placed next to the kiln.

Picture 55: A fire is lighted at the bottom of the kiln.

Picture 56: Progressively the kiln is filled with wood on top of the fire.

Picture 57: Progressively the kiln is filled with wood on top of the fire.

Picture 58: Progressively the kiln is filled with wood on top of the fire.
Picture 59: When no wood can be added, the kiln is ready to be sealed.

Picture 60: Smoke can be seen from far away.

Picture 61: Some charcoal makers fill the kiln before lighting the fire underneath.

Picture 62: The kiln is sealed and let down to cool.

Picture 63: Some kilns have a rectangular shape.

Picture 64: After cooling the drum can be opened.

Picture 65: The charcoal produced contains burned wood & ashes.

Picture 66: Charcoal is put in bags.
3.3.2 Namibian Retort

3.3.2.1 Principle

Some individuals have developed retort types kilns, to increase the productivity of their charcoal production. The operating principle of this retort kiln is shown in Figure 7. The different steps of the method are illustrated by Picture 67 to Picture 78.

The Namibian retort consists of a metal cylindrical enclosure inside which is fixed the retort, also of cylindrical shape. The retort is filled by wood logs before being sealed and heated by a fire underneath. The hot combustion gases escape along the walls of the retort which allows to increase the temperature of the inside wood. After some time, the water in the wood turns to steam and the pressure in the chamber increases, a gas stream is then generated to the chimney of the retort. When the wood is dry, all water being removed, pyrolysis begins and fuel gases are produced. When they exit the chimney, they ignite due to the contact with air. The information given by the designers of this retort indicates that the combustion of these gases should take place in the chimney which has an air access at its base. The heat released by this combustion is supposed to provide enough energy to maintain the pyrolysis. However, several observations indicate that this is probably not the case: the burning of gas takes place only a few centimetres above the chimney output, flue gases coming through the orifice at the base of the chimney probably contain too little oxygen as they come from the combustion chamber. Finally, when the fire under the retort is not powerful enough, the carbonization process in the retort stops, without the entire wood load being carbonized.

To improve the drying conditions in the retort and decrease the duration of this phase, junctions between the inside of the retort and the outside air have been arranged at the base of the retort. The objective is to enable the creation of a drying flow in the retort and to more rapidly reach the pyrolysis conditions.

This Namibian Retort has a good image among users: high productivity and a high-quality charcoal product are two of its advantages over traditional kiln. Moreover, this alternative is movable.

3.3.2.2 Namibian retort, in brief

- Mobile
- Less Cheap ($7,000 N\$)
- Shorter lifetime (unknown but less than 1 year for the bottom metal plate)
- Supposed high yield
- Generates less smoke but still some
- Charcoal contains no sand & ash
- Stable production (very good charcoal)
- Quality & yield depends less on “charcoal maker’s skills”
- Needs fuel wood
- One day process

Figure 7: Namibian retort principle
After being loaded, the pot is sealed.

The wood contained in the retort is heated.

Heating phase

Steam starts to exit the retort pot.

Steam flow is increasing.

Steam flow starts mix with pyrolysis gas.

The gas leaving the retort is flammable.

Exhaust gas burns in contact with air.
3.3.1 Other kilns

During this mission, other carbonization kilns were observed. A very large retort oven which is no longer in use (Picture 79) was part of a set of 4 which were spread across different farms. In Otjiwarango, a Ukrainian retort oven is being assembled; it was purchased by the Cheetah Conservation Fund and is intended for carbonization of densified bush briquettes already produced by this organization (Picture 80 & Picture 81). There is also one (or more) brick furnace in the Otjiwarongo area. However, these have not been visited. According to information obtained, it could be a hemispherical Brazilian kiln.
3.3.2 Stakeholders expectations regarding a new charcoal production technique
Meetings and discussions with charcoal industry stakeholders, together with field observations have highlighted the following aspects to be considered when designing a new charcoal production system:

<table>
<thead>
<tr>
<th>Expectations</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>A cleaner system that generates less smoke</td>
<td>The lifetime of current furnaces is from 10 to 15 years</td>
</tr>
<tr>
<td>Mobile or semi-mobile technology</td>
<td>Drying leads to higher yields of carbonization but is impractical at mobile sites</td>
</tr>
<tr>
<td>Small scale</td>
<td>The productivity of a drum is 200 - 250 kg / week</td>
</tr>
<tr>
<td>Faster carbonization process (1 day)</td>
<td>N$ 2,000 investment for one kiln</td>
</tr>
<tr>
<td>Improved charcoal quality</td>
<td></td>
</tr>
<tr>
<td>Improved charcoal resistance to transport</td>
<td></td>
</tr>
<tr>
<td>Reuse of existing equipment</td>
<td></td>
</tr>
<tr>
<td>Reduced fire risk</td>
<td></td>
</tr>
</tbody>
</table>

3.4 Namibian wood & charcoal characteristics

3.4.1 Wood moisture content
The high temperatures during daytime, the low relative air humidity and the strong winds offer favourable drying conditions. According to collected information, the harvested wood can therefore reach an equilibrium moisture content of 15% or less. It seems that for medium size wood this moisture level may be achieved within 3 to 4 months. However, this estimate should be confirmed by measurements and the establishment of wood drying curves.
According to data gathered during this mission, the wood moisture content at harvesting is higher than 42%, which is the maximum limit of detection of the used hygrometer. This range of value is not surprising, wood moisture just after harvesting is generally around 50%.
A high proportion of harvested wood is made up of branches or dead trees. In addition, it takes several days between the time of harvesting and carbonization, under very favourable conditions for air drying. Accordingly, the wood’s initial moisture content prior to carbonization has been estimated to be 30%. This value must be confirmed by additional measurements of wood dried in a drying cabinet.

3.4.2 Wood ash content
The pure wood ash content of wood is generally very low (about 0.5%). The bark ash content is higher and may reach 5%. The origin of these ashes is twofold: the minerals contained in the bark and the external particles that adhere to bark during tree growth and harvesting. In Namibia, the wood is not debarked, is of small diameter, and the ground is dry and often sandy, leading to high levels of ash in the harvested wood. Ash contents of 6 to 7% or more were mentioned for wood. It should nevertheless be noted that these values are in contradiction with the ash content of charcoal mentioned in the analyses reports provided by processors (Table 4). The average value mentioned in the analysis reports is 6.2%, and charcoal has a higher ash content than the wood it is made of.

3.4.3 Log bulk densities
Bush invasive species (Dichrostachys cinerea, Acacia mellifera, Acacia reficiens, Prunoides terminalia, Combretum apiculatum, C. mopane, Combretum sp, Acacia senegalensis...) have very high particle densities, although it is difficult to find accurate data on this subject.
By default, in this report, the value considered for particle density will be 770 kg/m³ dry. If logs are piled in 1 m long pieces, given the rough and tortuous nature of these species’ bark and the average diameter of the branches, it seems realistic to consider a piling factor of 0.6. Thus, one cubic meter of
piled logs contain about 462 kg of dry wood. The piling factor will be 0.3 for the filling of a cylindrical carbonization kiln. A kiln having a volume of one cubic meter will only contain 231 kg of dry wood.

3.4.4 Charcoal Moisture Content

Like wood, the charcoal moisture content stabilizes approximately at air moisture content. However, charcoal reaches a lower moisture content than wood. According to the data provided by the processors, charcoal moisture content at equilibrium would be around 1%. (Table 4).

3.4.5 Charcoal ash content

The traditional method of charcoal making in Namibia generates a lot of ash: wood logs are burned one above the other and charcoal in the bottom of the kiln is polluted by sand (Table 4).

3.4.6 Charcoal density

Table 4: Charcoal & briquettes characteristics, based on data provided by Carbo Namibia & Makara Bush Products

<table>
<thead>
<tr>
<th>Lumpy Charcoal</th>
<th>1 + 2 + 3</th>
<th>Vol Mat (2)</th>
<th>Fix Carb (3)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC2078</td>
<td>0.82</td>
<td>7.8</td>
<td>18.05</td>
<td>74.15</td>
</tr>
<tr>
<td>HC2080</td>
<td>1.28</td>
<td>6.42</td>
<td>14.28</td>
<td>79.29</td>
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<tr>
<td>HC2079</td>
<td>1.15</td>
<td>7.88</td>
<td>23.1</td>
<td>68.02</td>
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<tr>
<td>HC2036</td>
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<td>4.74</td>
<td>7.31</td>
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<tr>
<td>HC2258</td>
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<td>6.95</td>
<td>16.12</td>
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<tr>
<td>HC2233</td>
<td>0.97</td>
<td>1.87</td>
<td>8.32</td>
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<td>HC2268</td>
<td>0.47</td>
<td>7.43</td>
<td>19.31</td>
<td>73.25</td>
</tr>
</tbody>
</table>

Mean 1.0 6.2 15.2 78.6
Std 0.3 2.2 5.8 7.7
CV 29.0 35.3 37.8 9.8

The charcoal particle density depends on the wood density from which it was produced. Forest species of Namibia are characterized by high density; as is the resulting charcoal (Table 4).

3.4.7 Charcoal size classes & prices

The charcoal classes after sorting were presented in section 3.2.2. It gives an indication about the current situation. As retort charcoal has no contact with the soil, as it undergoes no combustion and no settlement during production, retort charcoal pieces will be of larger dimension and free of the "Sand & Ash" fraction. As a consequence, the different classes’ proportions are modified. The data presented in Figure 6 were therefore recalculated accordingly and are presented in Figure 8.

Consequently, the charcoal bulk price is changed. The current price structure is shown in
Table 5.
Table 6 & Table 7 present two hypotheses for the charcoal price evolution, depending on the quality: the first option maintains the same price levels for different classes, but allows for redistribution, in this case the price of charcoal in bulk will be N$ 1.860/tonne. This assumption is deemed too pessimistic by many stakeholders who considered the two best charcoal classes will reach a price of N$ 3.000 / tonne. In this case the price of charcoal in bulk will be N$ 2.550/tonne.
Table 5: Actual shares & prices for charcoal size categories

<table>
<thead>
<tr>
<th>Classes</th>
<th>Central point</th>
<th>%</th>
<th>Cumulated</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 5</td>
<td>2.5</td>
<td>6.0</td>
<td>6.0</td>
<td>0 N$/Ton</td>
</tr>
<tr>
<td>5 to 20</td>
<td>12.5</td>
<td>28.0</td>
<td>34.0</td>
<td>750 N$/Ton</td>
</tr>
<tr>
<td>20 to 60</td>
<td>40</td>
<td>60.0</td>
<td>94.0</td>
<td>1850 N$/Ton</td>
</tr>
<tr>
<td>60 +</td>
<td>75</td>
<td>6.0</td>
<td>100.0</td>
<td>3000 N$/Ton</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Bulk price | 1500 N$/Ton |

Table 6: Expected shares & prices for retort charcoal size categories – Hypothesis 1

<table>
<thead>
<tr>
<th>Expected size distribution from retorts</th>
<th>Central point</th>
<th>%</th>
<th>Cumulated</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 5</td>
<td>2.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0 N$/Ton</td>
</tr>
<tr>
<td>5 to 20</td>
<td>12.5</td>
<td>20.0</td>
<td>20.0</td>
<td>750 N$/Ton</td>
</tr>
<tr>
<td>20 to 60</td>
<td>40</td>
<td>60.0</td>
<td>80.0</td>
<td>1850 N$/Ton</td>
</tr>
<tr>
<td>60 +</td>
<td>75</td>
<td>20.0</td>
<td>100.0</td>
<td>3000 N$/Ton</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Bulk price | 1860 N$/Ton |

Table 7: Expected shares & prices for retort charcoal size categories – Hypothesis 2

<table>
<thead>
<tr>
<th>Expected size distribution from retorts</th>
<th>Central point</th>
<th>%</th>
<th>Cumulated</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 5</td>
<td>2.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0 N$/Ton</td>
</tr>
<tr>
<td>5 to 20</td>
<td>12.5</td>
<td>20.0</td>
<td>20.0</td>
<td>750 N$/Ton</td>
</tr>
<tr>
<td>20 to 60</td>
<td>40</td>
<td>60.0</td>
<td>80.0</td>
<td>3000 N$/Ton</td>
</tr>
<tr>
<td>60 +</td>
<td>75</td>
<td>20.0</td>
<td>100.0</td>
<td>3000 N$/Ton</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Bulk price | 2550 N$/Ton |

4 Kiln testing

4.1 Test description

During this mission 5 yields tests of the Namibian retort kiln were performed. These tests were performed at the production sites of two different charcoal producers. In addition, 6 tests of the Namibian traditional kiln were performed, also at two production sites. The method of these tests is illustrated in Picture 82 to Picture 88. The method used to determine the mass of wood used for each carbonization cycle consist in weighing more logs than needed for each cycle. The remaining wood is weighed after the kiln is closed. This procedure allows, once the weighing work is finished, to let charcoal makers work as they usually do, without interfering. It was used for both tests of traditional kilns and of the retorts kilns.

Moisture content measurements were conducted with a portable electric hygrometer. Based on these measurements, the initial moisture of the batch was estimated to be 30%. The ‘average’ moisture content before carbonization should be confirmed by a larger number of measurements, a more rigorous sampling and complemented by moisture content measurements in a drying cabinet. The duration of the mission did not allow to conduct a substantial number of measurements. When carbonization is complete and the kiln is cooled, the kiln is discharged, charcoal is bagged and bags are weighed. The considered moisture content for charcoal is 1%. The mass...
yield is calculated using the formula presented in section 2.3

4.2 Results & discussion

4.2.1 Measured values & yields

Figure 9 shows the mass of the initial wood load ($M_{ba}$, as defined in section 2.3) for traditional and retort kilns. A carbonization cycle with the traditional kiln requires around 792 kg of dry wood. The cycle lasts 6 days. The capacity of the retort kiln is about 281 kg per cycle, the cycle takes 24 hours. A retort oven could thus transform 1 686 kg wood within 6 days, almost double the capacity of the traditional kiln. The amount of fuel wood needed for combustion (246 kg / cycle on average) has to be added and is
Figure 10 illustrates the amount of charcoal produced per cycle ($M_{ca}$, as defined in section 2.3). Traditional kilns produce 270 kg charcoal on average every 6 days, while the retort kilns produce 119 kg per day, or 714 kg charcoal every 6 days. Therefore, the productivity per kiln of retort furnaces is 2.6 times higher than that of traditional kilns.

Based on the 6 tests performed, the estimated yield for the traditional kiln is on average 33.5%. The yield of retort kilns (based on 5 tests) was on average 26.4%. The results are highly variable. If the fuel wood is not considered, the retort mass yield is 42%. Figure 11 shows the calculated mass yields ($RM_{ba}$, as defined in section 2.3) based on data collected in the field.

It should be noted that the observed yield for traditional kilns is very surprising and is far above yields usually recorded with this type of kiln.

Regarding the retort kiln mass yield, it should be noted that the wood fuel has been taken into consideration in the calculation (global yield). Moreover the tests had certain limitations: wood load moisture content, which was considered to be around 30%, according to measurements and information collected on the field. An overestimation of the moisture content also leads to an overestimation of yield. But the impact of this potential source of error is limited. Similarly, a low fixed carbon content may partially explain the high yield of traditional retorts. Samples were taken for analysis of the fixed carbon content. The reloading process during carbonization may also affect performance, but it is difficult to quantify this impact. Also, the influence of the high particle densities of the carbonized species on mass yield should be evaluated.

4.2.2 Environmental impact

It was shown in section 2.5 that emissions related to carbonization are depending on the yield. Applying the same calculation method, but considering the Namibian traditional kiln as the reference, the results are different. Table 8 shows the estimation of these emissions considering that for the Namibian traditional kiln 2.5% of the carbon is emitted in the form of methane, and the remaining carbon is emitted as CO$_2$. For GMDR & Mindourou kilns, it is considered that only 0.2% of...
the Carbon emitted is methane. In this case the use of a GMDR saves 1,75 tonnes of CO₂ equivalent per produced tonne of charcoal while the Mindourou kiln leads to avoid the emission of 1,62 tonne CO₂ equivalent.

The low overall yield (including fuel wood) of the Namibian retort furnace leads (if it is considered that 0,75% of the emitted carbon is CH₄) to higher CO₂ equivalent emissions in the atmosphere than for the traditional kiln. Indeed, the production of one tonne of charcoal with the Namibian retort kiln release 1,02 tonne CO₂ equivalent more than if it had been produced with the traditional kiln.

It must be noted that the methane amount contained in the gases emitted by the Namibian retort was set at 0,75% by hypothesis, based on qualitative field observations. In the future, this aspect will need to be confirmed by measurements to accurately determine the environmental impact of this retort, particularly if measures are undertaken to improve its performance.

For information, as another hypothesis, at the current state of performance of the Namibian retort kiln, if all methane is considered as combusted (i.e. 0% CH₄ in gas escaping from the kiln), this alternative still would emit 0,39 tonnes equivalent CO₂ more than traditional kilns, per tonne of charcoal produced. If the CH₄ concentration was 1 or 2%, extra emissions are 1,23 and 2,45 T CO₂ eq per tonne of produced charcoal respectively.

Table 8: Emissions saving compared to Namibian Traditional drum for the Namibian retort, the GMDR & the Mindourou kiln.

### Table 8: Environmental impact of charcoal processes

<table>
<thead>
<tr>
<th>Material (MP) / Product (P)</th>
<th>Charcoal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonization Process</td>
<td></td>
</tr>
<tr>
<td>Carbonization characteristic</td>
<td></td>
</tr>
<tr>
<td>Proportion of C released under Methane form</td>
<td>% of released C</td>
</tr>
<tr>
<td>Proportion of C released under CO₂ form or eq % of released C</td>
<td></td>
</tr>
<tr>
<td>Anhydrous load wood mass (MP)</td>
<td>kg</td>
</tr>
<tr>
<td>Carbon proportion in MP %</td>
<td></td>
</tr>
<tr>
<td>MP Carbon Mass kg</td>
<td></td>
</tr>
<tr>
<td>Carbonization yield %</td>
<td></td>
</tr>
<tr>
<td>Charcoal Mass kg</td>
<td></td>
</tr>
<tr>
<td>Fixed Carbon proportion in Charcoal %</td>
<td></td>
</tr>
<tr>
<td>Carbon mass in charcoal kg</td>
<td></td>
</tr>
<tr>
<td>Carbon emission due to charcoal production kg</td>
<td></td>
</tr>
<tr>
<td>Spécific emissions kg/tonne Charcoal</td>
<td></td>
</tr>
<tr>
<td>Avoided emissions kg/tonne Charcoal</td>
<td></td>
</tr>
<tr>
<td>Minimum GHG reduction per tonne Charcoal cC/T CO₂ eq/tonne Charcoal</td>
<td></td>
</tr>
</tbody>
</table>

### 4.2.3 Financial evaluation

Table 9 summarizes the main characteristics of the considered alternatives for replication by a pilot. This data is used in Table 10 to estimate the income generated by the selected kilns. For this first analysis, it was considered that the increased quality of produced charcoal would lead to an increase in its price. A discussion with stakeholders has led to an estimated price of N$ 2.550 per tonne. The influence of the bulk charcoal sales prices will be discussed in §4.2.4

Given the carbonization chamber volume, the mass which it may contain, the carbonization yield and the carbonisation cycle time, it is possible to calculate the daily charcoal productivity for each alternative. It is estimated at 43 kg, 119 kg, 208 kg and 322 kg for the Namibian traditional kiln, the Namibian retort, the GMDR and the Mindourou kiln, respectively.
However, the investments related to charcoal production alternatives differ substantially. If productivities are compared on an equivalent investment basis (the one for Namibian traditional kiln), the trend reverses. Thus, an investment of N$ 2,000 generates 43 kg, 34 kg, 22 kg & 24 kg per day for the Namibian traditional kiln, the Namibian retort, the GMDR and the Mindourou kiln, respectively. It appears that the productivity increase of ‘improved’ alternatives to the Namibian retort cannot compensate the increased investment they impose.

However, if the price difference between the charcoal qualities is considered, income generated by an investment of N$ 2,000, are 65, 87, 56 & 62 N$/day for the Namibian traditional kiln, the Namibian retort, the GMDR and the Mindourou kiln, respectively. In this case, the Namibian retort is ranked at the top because it generates N$ 87/day.

Environmental impact must also be considered. Indeed, compared to the Namibian traditional kiln, the Namibian retort has higher emissions, 1,02 tonnes of CO₂ equivalent more, for each tonne of charcoal produced. On the other hand, the GMDR avoids the emission of 1,75 tonnes of CO₂ equivalent and the Mindourou kiln 1,62 tonne.

If the avoided emissions could be traded on the carbon market, currently a tonne CO₂ equivalent could be traded at around € 8. This aspect does not change the ranking of revenues generated by the different alternatives, the Namibian retort is, given assumption made about charcoal prices, the most productive solution. However, its negative impact on the environment prevents promotion of this alternative at its current stage of development.

### Table 9: Main characteristics of the considered kilns

<table>
<thead>
<tr>
<th>Kiln characteristics</th>
<th>Traditional Kiln</th>
<th>Namibian Retort</th>
<th>Green Mad Retort</th>
<th>Mindourou Kiln</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Material</td>
<td>Metal</td>
<td>Metal</td>
<td>Bricks</td>
<td>Bricks &amp; metal</td>
</tr>
<tr>
<td>Yield with fuel (%)</td>
<td>34</td>
<td>26</td>
<td>38</td>
<td>37</td>
</tr>
<tr>
<td>Volume m³</td>
<td>1,30</td>
<td>2,0</td>
<td>13,8</td>
<td>14,4</td>
</tr>
<tr>
<td>Productivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonisation time</td>
<td>6 days</td>
<td>1 day</td>
<td>5 days</td>
<td>5 days</td>
</tr>
<tr>
<td>Wood load kg/cycle</td>
<td>766,5</td>
<td>281</td>
<td>2695</td>
<td>4241</td>
</tr>
<tr>
<td>Wood load %</td>
<td>34</td>
<td>42</td>
<td>39</td>
<td>38</td>
</tr>
<tr>
<td>Yield without fuel kg/ton</td>
<td>119 kg Charcoal</td>
<td>1040 kg Charcoal</td>
<td>1610 kg Charcoal</td>
<td></td>
</tr>
<tr>
<td>Price N$/kg</td>
<td>1,5</td>
<td>2,4</td>
<td>2,8</td>
<td>2,7</td>
</tr>
<tr>
<td>Income generated/ day &amp; 2000 N$ invest N$/day &amp; 2000 $ invest</td>
<td>65</td>
<td>82</td>
<td>61</td>
<td>67</td>
</tr>
</tbody>
</table>

### Table 10: Estimation of incomes generated by the selected alternatives

<table>
<thead>
<tr>
<th>Kiln characteristics</th>
<th>Units</th>
<th>Namibian Drum</th>
<th>Namibian Retort</th>
<th>Green Mad Retort</th>
<th>Mindourou Kiln</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Metal</td>
<td>Metal</td>
<td>Bricks</td>
<td>Bricks &amp; metal</td>
<td></td>
</tr>
<tr>
<td>Yield with fuel (%)</td>
<td>34</td>
<td>26</td>
<td>38</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Volume m³</td>
<td>1,30</td>
<td>2,0</td>
<td>13,8</td>
<td>14,4</td>
<td></td>
</tr>
<tr>
<td>Productivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonisation time</td>
<td>6 days</td>
<td>1 day</td>
<td>5 days</td>
<td>5 days</td>
<td></td>
</tr>
<tr>
<td>Wood load kg/cycle</td>
<td>766,5</td>
<td>281</td>
<td>2695</td>
<td>4241</td>
<td></td>
</tr>
<tr>
<td>Wood load %</td>
<td>34</td>
<td>42</td>
<td>39</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Yield without fuel kg/ton</td>
<td>119 kg Charcoal</td>
<td>1040 kg Charcoal</td>
<td>1610 kg Charcoal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price N$/kg</td>
<td>1,5</td>
<td>2,4</td>
<td>2,8</td>
<td>2,7</td>
<td></td>
</tr>
<tr>
<td>Income generated/ day &amp; 2000 N$ invest N$/day &amp; 2000 $ invest</td>
<td>65</td>
<td>82</td>
<td>61</td>
<td>67</td>
<td></td>
</tr>
</tbody>
</table>
4.2.4 Sensitivity analysis

The main factors for improving the Namibian retort competitiveness, which will make it suitable for implementation and promotion by a pilot project, are: the global mass yield (including wood fuel), the sales price of charcoal in bulk and the methane concentration in emitted gases. Table 11 presents projections of generated incomes by a retort kiln based on increasing yields and compares it to the existing alternatives. Associated emissions are presented as well. Two assumptions for flue gas methane concentration are considered (0.2% & 0.75%). The estimation also considers the possibility to sell the avoided T CO₂ eq at a price of € 8 (N$ 123.2).

Table 11: Incomes generated per day by 2.000 N$ investment in NTK (Namibian Traditional Drum), GMDR (Green Mad Retort), MK (Mindourou Kiln) & NRK (Namibian Retort Kiln) & related CO₂ equivalent emissions or savings (tonne CO₂ eq / tonne charcoal). NTK being the baseline - same calculation procedure as for Table 10

<table>
<thead>
<tr>
<th>Prices hypothesis</th>
<th>Existing Kilns</th>
<th>NRK Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiln</td>
<td>NTK GMDR MK NRK</td>
<td>NRK NRK NRK NRK</td>
</tr>
<tr>
<td>Mass yield (%)</td>
<td></td>
<td>34 38 37 26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 35 40</td>
</tr>
<tr>
<td>Flue gases CH₄ concentration hypothesis 1</td>
<td>2.5 0.2 0.2 0.75</td>
<td>0.75 0.75 0.75</td>
</tr>
<tr>
<td>Related Avoided CO₂</td>
<td>T CO₂eq/T charcoal</td>
<td>0 1.75 1.62 -1.02</td>
</tr>
<tr>
<td>GQ Charcoal price (N$/ton)</td>
<td>63 63 63 63</td>
<td>85 85 85 85</td>
</tr>
<tr>
<td></td>
<td>1850</td>
<td>65 40 45</td>
</tr>
<tr>
<td></td>
<td>1900</td>
<td>65 42 46</td>
</tr>
<tr>
<td></td>
<td>2250</td>
<td>65 49 55</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>65 55 61</td>
</tr>
<tr>
<td>Price for avoided CO₂</td>
<td>63 63 63 63</td>
<td>85 85 85 85</td>
</tr>
<tr>
<td>tonne = 0</td>
<td>1850</td>
<td>65 40 45</td>
</tr>
<tr>
<td></td>
<td>1900</td>
<td>65 42 46</td>
</tr>
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<td>65 49 55</td>
</tr>
<tr>
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<td>2500</td>
<td>65 55 61</td>
</tr>
<tr>
<td>Flue gases CH₄ concentration hypothesis 1</td>
<td>2.5 0.2 0.2 0.75</td>
<td>0.75 0.75 0.75</td>
</tr>
<tr>
<td>Related Avoided CO₂</td>
<td>T CO₂eq/T charcoal</td>
<td>0 1.75 1.62 -1.02</td>
</tr>
<tr>
<td>GQ Charcoal price (N$/ton)</td>
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</tr>
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<td>1900</td>
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<td>65 49 55</td>
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<tr>
<td></td>
<td>2500</td>
<td>65 55 61</td>
</tr>
<tr>
<td>Price for avoided CO₂</td>
<td>63 63 63 63</td>
<td>85 85 85 85</td>
</tr>
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<td>tonne = N$123,2</td>
<td>1850</td>
<td>65 40 45</td>
</tr>
<tr>
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<td>1900</td>
<td>65 42 46</td>
</tr>
<tr>
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<td>2250</td>
<td>65 49 55</td>
</tr>
<tr>
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<tr>
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<td>0.2 0.2 0.2</td>
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<tr>
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<td>T CO₂eq/T charcoal</td>
<td>0 1.75 1.62 -0.56</td>
</tr>
<tr>
<td>GQ Charcoal price (N$/ton)</td>
<td>65 67 70 70</td>
<td>85 89 92 92</td>
</tr>
<tr>
<td></td>
<td>1850</td>
<td>65 40 45</td>
</tr>
<tr>
<td></td>
<td>1900</td>
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</tr>
<tr>
<td></td>
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<td>65 49 55</td>
</tr>
<tr>
<td></td>
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<td>65 55 61</td>
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<td>Price for avoided CO₂</td>
<td>65 67 70 70</td>
<td>85 89 92 92</td>
</tr>
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<td>tonne = N$123,2</td>
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<td>65 40 45</td>
</tr>
<tr>
<td></td>
<td>1900</td>
<td>65 42 46</td>
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<td></td>
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<tr>
<td></td>
<td>2500</td>
<td>65 55 61</td>
</tr>
<tr>
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<td>0.2 0.2 0.2</td>
</tr>
<tr>
<td>Related Avoided CO₂</td>
<td>T CO₂eq/T charcoal</td>
<td>0 1.75 1.62 -0.56</td>
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<tr>
<td>GQ Charcoal price (N$/ton)</td>
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<td>85 89 92 92</td>
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<td></td>
<td>1850</td>
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<td></td>
<td>1900</td>
<td>65 42 46</td>
</tr>
<tr>
<td></td>
<td>2250</td>
<td>65 49 55</td>
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<tr>
<td></td>
<td>2500</td>
<td>65 55 61</td>
</tr>
<tr>
<td>Price for avoided CO₂</td>
<td>65 67 70 70</td>
<td>85 89 92 92</td>
</tr>
<tr>
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The Table 11 central column (existing kilns) shows the results for the Namibian traditional kiln, the GMDR, the Mindourou kiln & the Namibian retort kiln considering the present yield. The right-hand column shows calculations for three yield assumptions of the Namibian retort. These assumptions are 30% yield which probably corresponds to the level of performance that can be expected by improving the current single retort kiln (see recommendation at § 6.1). The latter two assumptions (35 and 40% yields) estimate the performance levels that can be expected if further improvements are made, i.e. several kilns heating each other (see recommendation at §6.2). The first observation is that the global yield increase does not affect the Namibian retort productivity, because the productivity only depends on the yield without fuel. The yield without fuel is currently 42% and will likely not be increased. But, the global yield greatly influences the environmental impact. The increase from 26% to a 30% yield would place the Namibian retort to comparable emission levels than those emitted by the traditional kiln, while having a higher productivity.
Two assumptions about flue gas methane concentration were considered (0.75% based on qualitative field observation and 0.2% which seems a realistic target for a system of connected retort kilns). Each row of Table 11 (delimited by bold lines) also shows the effect of other factors influencing the carbonisation incomes. The first row considers no incomes from carbon markets (price for the CO₂ tonne = 0). It also assumes the CH₄ flue gas concentration is 0.75% and distinguishes four hypotheses for bulk charcoal prices: N$ 1850, N$ 1900, N$ 2250 & N$ 2500 per tonne charcoal. The N$1.850/tonne price considers the redistribution of “sand & ash” fraction on the other fractions and the three other price levels consider a price increase due to improved charcoal quality. The two next rows are based on the hypotheses of a price of € 8/tonne CO₂ equivalent, moreover row 2 is based on the hypothesis of 0.75 % CH₄ concentration in NRK flue gases, while it is 0.2 % in row 3. The same charcoal price hypotheses as for the first row are made in the second and third rows. The following examples are intended to further illustrate the results shown in the table.

**Example 1**: column 3 row 1, a 0.75% methane concentration and a yield of 35% would avoid the emission of 1.06 tonnes of CO₂ equivalent per produced tonne of charcoal (calculation based on Table 8 procedure). In these conditions, if the price per tonne CO₂ equivalent is € 0 (N$ 0) and the charcoal price is N$ 2.250/tonne; each N$ 2.000 investment would generate a daily income of N$ 77.

**Example 2**: column 3 row 2, a 0.75% methane concentration and a yield of 35% would avoid the emission of 1.06 tonnes of CO₂ equivalent per produced tonne of charcoal (calculation based on Table 8 procedure). In these conditions, if the price per tonne CO₂ equivalent is € 8 (N$ 123,2) and the charcoal price is N$ 2.250/tonne; each N$ 2.000 investment would generate a daily income of N$ 81.

**Example 3**: column 3 row 3, a 0.2% methane concentration and a yield of 35% would avoid the emission of 1.32 tonnes of CO₂ equivalent per produced tonne of charcoal (calculation based on Table 8 procedure). In these conditions, if the price per tonne CO₂ equivalent is € 8 (N$ 123,2) and the charcoal price is N$ 2.250/tonne; each N$ 2.000 investment would generate a daily income of N$ 82.

If no marketing of avoided CO₂ is considered, it appears that the Namibian retort is competitive with the traditional kiln from a price of good quality charcoal of N$ 1.900/tonne. However, it is likely that charcoal quality allows to sell the production at higher prices, about 2.250-2.500 N$/tonne. Incomes generated by N$ 2.000 investment are of N$ 65, N$ 77, N$ 85 if the bulk prices are 1.900, 2.250 & 2.500 N$/tonne, respectively.
5 Conclusions

† The high mass yield (34%) of the Traditional Namibian Kiln has been a surprise:
   † It is higher than expected for this type of kilns.
   † Its low cost and long life time makes it a highly competitive alternative.
   † But its use leads to pollution.
   † And it produces a charcoal of inferior quality, that could be easily improved

† The high Quality of the Namibian Retort Kiln charcoal and its short production cycle (1 day) makes this alternative more profitable than the Namibian Traditional Kilns
   † But it has a far lower global mass yield.
   † It leads to higher greenhouse gas emissions as well.
   † These 2 weak points make it difficult to promote de Namibian Retort Kiln at its current stage of development.

† Among the alternatives selected, the only proven technology that has a better impact on the environment compared to the Namibian traditional Kiln is the GMDR:
   † But it is the less profitable solution.
   † It is an immobile alternative (which has many advantages but is not what the main share of charcoal producers expects).
   † Anyway, there is a demand for brick kilns and this alternative should be demonstrated in a pilot project.

† Finally, major improvements of the Namibian charcoal production chain can be achieved through the further development of the Namibian Retort Kiln:
   † An improvement of 10% of its global yield would makes this alternative more environmental friendly than the traditional kiln
     † These developments and related experimental planning are described in section 6.1
   † The combination of a few Namibian Retort Kilns would allow to use the heat generated by the combustion of the pyrolysis gases of one retort to heat the next one
     † This achievement should decrease the amount of wood fuel needed per carbonization and by that increase the mass yield. A realistic yield assumption would be between 35 and 40%. The effect of these yield improvements are presented in Table 11.
     † The retort should be developed as modular structure that could be used alone or as a combination of two or more kilns, without maximum limit.
     † This improvement will lead to avoided or drastically reduced use of fuel wood which is responsible of the low yield of this alternative.
     † This will place the Namibian Retort Kiln among the cleanest technologies for producing charcoal (high yield, emission burning, high quality charcoal).
     † Moreover, it would fulfill some of the producer requirements
       † Semi-mobility
       † Cleaner production
       † Higher quality
       † Affordable investments
       † Reuse of existing equipment...

† As a consequence, a pilot project should concentrate on:
   † Characterizing the baseline parameters (Namibian Traditional Drum)
     † CH₄ emissions
     † Yield confirmation (and accurate moisture content determination, carbon content)
   † Proposing alternatives
     † Namibian retort kiln development
A single kiln will probably at best reach the environmental efficiency of a Traditional kiln.

As series of kilns could lead to one of the cheapest and cleanest technologies for charcoal production.

Implement a GMDR demonstration unit, to:

- Confirm the implementing costs in Namibia
- Fulfil the demand for brick kilns of some producers
- Evaluate the yield of this alternative when using Namibian tree/bush species
- Compare the environmental efficiency in relation to the other alternatives
- Determine the advantages and drawbacks of a fixed alternative...

For both alternatives, efforts should concentrate on:

- Global yield improvement
- Emission measurements
- Wearing and maintenance costs determination
- Evaluate the advantages and drawbacks of mobile and semi-mobile alternatives...
6  Recommendations

6.1  Recommendation 1: Namibian retort improvement – Experimental planning proposal

6.1.1  Activities

These tests are designed to estimate the mass yield improvement due to small and simple modifications.

The tests will be conducted on modified retorts equipped with pipes of a 7-cm diameter

3 variation factors will be tested

- Pipes usefulness and time prior to closing influence
- Heating power
- Drying time

For each participating producer, these tests require 3 Namibian retorts equipped with 7cm diameter pipes.

1 to 3 participating producers

Experimental procedures

A data collection sheet for each participating producer is included in Annex 1 (the Excel file will be provided as well)

The first step is the wood harvesting

8 tonnes must be harvested each day during a 6-day period

- 2 tonnes have to be processed on the following day
- 2 tonnes must be dried for 1 week before being processed
- 2 tonnes must be dried for 1 month before being processed
- 2 tonnes must be dried for 2 months before being processed

Wood piles for drying must be clearly marked

The second step is to process the wood according to the table in Annex 1

The same treatment is applied to three retorts tested at the same time (3 repetitions per treatment)

Treatments are:

- Load moisture content modified by drying time of:

  - 1 day
  - 1 week
  - 1 month
  - 2 months

- Heat power during retort drying phase

  - Low: around 10 kg wood per hour
  - Around 30 kg wood/hour
  - Warning! as soon as the retort is closed heat power must be high (about 30 kg per hour)

  - The values of 10 or 30 kg of wood per hour may be adjusted if necessary based on field observations, but once established they must be kept for other tests

- Time before closing airpipes and lid

  - 0 hours (this treatment actual situation without air pipes, in this case the lid is closed as well)
  - 1 hour (for 1 hour air pipes & lid are left open)
  - 3 hours (for 3 hours, pipes & the lids are left open). If it appears that the 3 hours cause an excessive burning of the load, this period may be reduced and brought back to 2
hours. Please note this will then be made for all tests (including low heat power)

Recorded data are:

- The initial wood mass in the retort pot
  - Warning, the wood load must not include dead wood.
  - To estimate the initial wood mass of the load, the same procedure as that applied during the mission will be repeated: more wood than needed is weighed prior to loading and after loading. The mass of wood constituting the charge is obtained by deducting the remaining from the initial mass of wood.

- Initial wood load moisture content
  - Measurements are made using an electric hygrometer or ideally samples are taken in a drying cabinet.

- The wood fuel mass
  - Wood fuel may include dead wood.
  - The dead wood proportion has to be estimated.
  - To estimate the wood fuel mass, the same procedure as that applied during the mission will be repeated: more wood than needed is weighed prior and after burning (remaining wood). The mass of needed fuelwood is obtained by deducting the remaining from the initial mass of wood.

- Amount of produced charcoal
- Unburnt mass
- Ideally a charcoal sample is taken for fixed carbon content analysis.

At the end of the first week, the data can be sent to mike.temmerman@eco-consult.com for first analysis and confirmation of the further experimental planning with or without modifications.

6.1.2 Kiln size effect

- When the most effective kiln management procedure has been described, it will be tested on kilns of different sizes.
  - Half volume retort
  - Double volume retort

- Results will be compared to retorts tested at section 6.1.1

6.1.3 Implementation

- A harvest 8 tonnes of wood per day will require to hire about 5 experienced charcoal makers. These charcoal makers may have to be paid, because only a portion of the harvested wood (1/4) will be processed directly, the rest will undergo a drying period. For the last pile, the charcoal will be produced only 2 months later.
- 3 modified retorts / participating producers
- 1 half volume sized retort
- 1 double volume sized retort
- NCA follow up
  - Explanations and implementation of experimental design to participating producers
  - Contact & discussion with ECO
  - 2-man month needed
6.2 Recommendation 2: Namibian retorts combination

6.2.1 Activities

This development will propose a concept of optimized Namibian retort regarding productivity & environmental impact, to do this, the following steps need to be implemented:

Accurate base line characterization
- Yield confirmation for traditional Namibian kiln
  - accurate moisture content measurement (& sample)
  - determination of wood log diameter influence
  - attempt to explain high values
    - determination of carbonisation temperature profile
    - tests with species of different densities...
- Emission measurement for traditional Namibian kiln
- Estimated number of kilns in Namibia

Design of effective modular retort system
- In collaboration with a local workshop and based on the development results described in recommendation 1, a system will be designed which uses the heat from the gas combustion of a retort to power the following.
- This system must be modular: able to work as a single kiln but with the possibility to combine more than one kiln to improve the global efficiency and yield.
- The influencing factors are further investigated
  - Initial moisture content of wood load
  - Log diameter
  - Wood species’ particle densities
  - ...

When the modular system is developed, its use is optimized
- Influence of the carbonization time on the charcoal quality and transport resistance
- Determination of the number of modules and wood volumes required for continuous operation
- Depending on the wood initial moisture content, determine the minimum flame phase duration to carbonize the whole amount of wood (without unburnt)
- Determine the influence of the carbonization time (heating) on the fixed carbon content
- Determine the fixed carbon content providing the best balance quality / weight loss

The organisational setup of the operation is optimized
- Training for workers,
- Division of work,
- Logistics.

To better understand the Namibian retort kiln carbonization process, the following profiles will be established:
- Temperature (progression of the pyrolysis front)
- Fixed carbon content at the end of process

After system optimization
- Overall yield calculation, depending on the number of retorts included in the system
- Emission estimation
- Environmental benefit estimation when replacing the traditional system by the optimized retort system
- Financial & economic evaluation
- Planning of next steps for a large-scale distribution

Long-term follow-up (one year) to confirm the data about
- Wearing and maintenance cost
- Charcoal price evolution regarding the improved quality
6.2.2 **Implementation**

- International Expertise: 3-man months
- NCA involvement: 3 months
- NCA Follow up: 1 year
- Equipment and workshop: about 25 000€

6.3 **Recommendation 3: GMDR Set up and training for use**

The GMDR is a well-established technology that offers the best environmental performance among the considered solutions. Even though the level of investment required makes it uncompetitive compared to Namibian traditional kilns, it can however be used in the same conditions as brick kilns already used in Namibia (partly combusted wood load brick kilns).

The implementation of a demonstration GMDR will allow:

- To clarify its construction costs under Namibian conditions
- To assess the advantages and drawbacks of a centralized and fixed charcoal production alternative
- To evaluate the environmental benefit of this alternative and the productivity increase compared:
  - to brick kilns which are currently used,
  - to traditional drums.

6.4 **Sound selection of the charcoal process to promote**

The analysis of information collected from §6.1 to 6.3 will lead to the proposal on sound and clean charcoal production techniques adapted to the Namibian context. This alternative will be described in a promotional brochure which will put forward the following:

- Productivity increase
- Quality improvement and sale price increase
- Environmental improvement
- Possibility for charcoal producers to be assisted by NCA to design their carbonization equipment needs
- NCA possibility of assistance for bush harvesting planning and management in a perspective of charcoal production

7 **References**


### Annex 1: proposed experimental planning for the first phase

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<th>Estimated MC (%)</th>
<th>Charcoal mass (kg)</th>
<th>Uncooked wood mass (kg)</th>
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</tbody>
</table>