# Charcoal Making

## *Basic Principles*

- Wood in addition to any moisture content is mainly composed of cellulose, hemicellulose, and lignin which are compounds of carbon, hydrogen, and oxygen.
- Charcoal is mainly carbon. The process of making charcoal is that of converting wood into carbon, i.e. carbonization.
- Carbonization is the process of heating the wood to remove the moisture and to break down by pyrolysis the wood compounds into carbon plus a range of volatile compounds containing the hydrogen, oxygen, and some of the carbon.
- Although the process is sometimes referred to colloquially as “charcoal burning”, pyrolysis is quite distinct from complete combustion in which oxygen from the air combines with the wood compounds to eventually produce just carbon dioxide and water.
- The process of carbonization inherently involves the release of substantial amounts of volatile compounds which must be vented from the kiln.
- Removal of moisture takes place typically at temperatures of 110-150°C.
- Pyrolysis occurs at temperatures in the region of 260-380°C. Better purer charcoal is obtained with temperatures at the upper end of this range.
- The process of heating and removing moisture from the wood requires heat energy to be supplied, while the chemical reactions of pyrolysis are slightly exothermic, i.e. they release heat, but this is much less than that released by combustion.
- The process of carbonization can take place in the absence of air provided there is a source of heat, e.g. in a retort with external heating. In a kiln, however, heat is provided by burning directly within the kiln a proportion of the wood charge to be carbonized, and so a limited air supply is required.

## *Instructions for a Small Metal Kiln (1.2m diameter)*

### Positioning and setting up the kiln

1. Make sure the ground where the kiln is to be placed is roughly level.
2. Position the 4 metal air inlet channels and 4 air inlet/outlet channels (with fittings for the chimneys) alternately in a spoke pattern. The inner ends of the 4 inlet only channels should be fairly close to the centre of the base of the kiln. The 4 inlet/outlet channels can be skewed somewhat so the inner ends are further away from the centre of the kiln while the chimneys when fitted will still be right next to the kiln walls – this is to facilitate the “reverse draught” mode (see bullet 32 below).
3. Roll the kiln body into position on top the air inlet and outlet channels, ensuring that the gaps between the air channels are open all the way the round.

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### Creating the lighting channels

4. Place pairs of pieces of wood slightly thicker than the inlet and outlet channels between the channels to form stringers for lighting channels.

5. Pack the lighting channels with dry newspaper, kindling and firelighters. The newspaper and kindling can usefully be soaked in a moderately flammable liquid like cooking oil, but **not** a highly volatile flammable liquid such as white spirit, let alone explosively flammable petrol.
6. Place wood across the stringers to form the roof of the lighting channels - incompletely charred wood from the previous burn is ideal for this purpose.
7. Any spaces not yet used at the bottom of the kiln can be filled with more kindling or small pieces of wood aligned radially to the kiln.

As a simplification for the small kiln the wooden stringers can be dispensed with and all the space between the metal air channels filled with kindling etc. Pieces of wood to cover the kindling layer are placed across the metal air channels.
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## Preparing the wood charge

8. Use well seasoned wood if available.
9. Wood that has been air dried during the best time for drying, i.e. spring and early summer, is better than freshly cut wood.
10. Cut the wood short enough to fit in the kiln.
11. If stacking a layer of the charge vertically then cut the wood for that to a consistent length.
12. Cut larger diameter pieces shorter, especially if using freshly cut wood, so they can be placed in the hotter middle part of the kiln.
13. It is best to split the largest pieces (above 150mm diameter).
14. Don’t mix very large and very small diameter pieces in the same charge.

## Filling the kiln

15. Start filling the kiln with pieces of wood laid horizontally on top of the air inlet and outlet and lighting channels.
16. In line with the filling of traditional earth covered kilns the bulk of the kiln can optionally be filled with wood stacked vertically. This means that the material collapses more slowly during the burn, so maintaining lower resistance to the flow of gases through the kiln for longer.
17. Stack the wood vertically round a central pyramid arrangement outwards. This should make the stack collapse inwards away from the cooler wall of the kiln.
18. Place the larger diameter pieces of wood nearer the centre and towards the bottom of the kiln where it always gets hotter than the near the walls or the top.
19. Finish filling to the top of the kiln by stacking horizontally.
20. The kiln can be filled slightly above the top of the walls (up to 100mm) because the charge will sink before the lid needs to go on.

The usual advice is to pack the kiln as neatly as possible to maximise the amount of wood in the charge. However, it may be much quicker and less effort to not worry and just throw the wood in higgledy-piggledy. In this case wood can be stacked well above the top of the walls (up to300mm), because it will sink more as the burn gets underway.
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## Lighting and initial moisture removal

21. Set light to the lighting channels; starting with the channels on leeward side, and leaving a few minutes before lighting the channels on the windward side.

22. The quickest way to get the kiln to heat up is to leave the lid off until the carbonizing temperature is reached. This usually takes 30-60 minutes. There are a number of indicators of this temperature:
    - the wall of the kiln becomes much too hot to touch,
    - the rusty colour of the kiln wall darkens,
    - water will sizzle if splashed onto the kiln,
    - the kiln is too hot to stand close to comfortably, or
    - the copious steam billowing out of the kiln begins to be tinged with darker yellowish smoke.
23. It should be possible to light the wood at the top of the kiln by throwing on hot embers from the base – aim for near the kiln wall where the air isn't swamped by steam. Alternatively, the wood at the top may light spontaneously. Leave to burn for several minutes to ensure the upper part of the kiln gets really hot.
24. Once the kiln is hot enough lift the lid into position – if the top of the charge is alight, manoeuvre the lid using logs inserted into the handles. If the charge has sunk below the top of the kiln wall, sit the lid down on the lip just inside the rim of the kiln wall to put the flames out. If the top of the charge is still above the kiln wall, sit the lid down on the charge – if the top of the charge is already alight it may still flame around the edges for a while.
25. Insert a pair of logs across the top of the kiln wall, so as to leave a gap between the lid and the kiln wall all the way round. If the top of the wood charge is still above the kiln wall insert the logs to raise the lid above the charge – the charge will soon sink to leave the gap in the same way.

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## Controlling the charring of the wood

The process of charring the wood, i.e. carbonizing it, is one of controlling the air supply at the bottom of the kiln and the exhaust flow at the top, so as to maintain the temperature for pyrolysis. Precise control of the various air inlets and vents is required to even out temperature differences and hence charring rates in different parts of the kiln.

26. As the moisture evaporates and the wood dries out and the pyrolysis reactions progress, the carbonization process becomes progressively more exothermic, tending to increase the kiln temperature. To compensate for this the air inlets and the exhaust vents need to be progressively restricted.
27. Restrict the air supply progressively by:
    - first blocking up the spaces between the air inlet channels bit-by-bit with sand or soil, and
    - then blocking the 4 air inlet/outlets, leaving just the 4 air inlets open.
28. Restrict the exhaust progressively by:
    - first removing the spacing logs and lowering the lid on to the kiln wall,
    - then sealing the perimeter of the lid with sand/soil, and
    - then partially covering the 4 steam vents on the lid.
29. Sand (e.g. conventional building sand) is much more effective at sealing than soil – organic matter in top soil may burn, while clay will shrink as it dries out.
30. To limit the difference in temperature between the top and bottom of the kiln the progressive steps to restrict the air supply should be applied slightly ahead of those to restrict the exhaust.

31. To avoid the side of the kiln facing the prevailing wind getting hotter and carbonization of the wood on this side finishing before the rest of the wood the inlets and vents should be restricted on the windward side first.
32. The most restricted state of the kiln which still allows pyrolysis is the so-called “reverse draught” mode. This is achieved by fitting the 4 chimneys to the inlet/outlet channels and closing the steam vents on the lid by covering and sealing with sand/soil. In this mode gases circulate upwards in the hotter middle part of the kiln and then sink down near the walls before being vented through the outlet channels and chimneys. The chimneys will draw once they have warmed up by being adjacent to the hot kiln wall – this usually takes 5-10 minutes. For a small kiln the gas flow in the reverse draught mode is insufficient to maintain adequate carbonization temperature except towards the very end of the pyrolysis phase.
33. In the “reverse draught” mode some chimneys may not draw properly. Sometimes a chimney position can be made to draw by swapping the chimney with one which is already hot from gases venting through it.
34. The process of charring the wood takes 5-7 hours in the small kiln depending on the degree of air supply and exhaust restriction applied.

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## Shutting down the kiln

As the drying out and pyrolysis phase progresses the exhaust changes from the white of mostly steam to a thicker, darker, yellowish smoke, and finally to a clearer, thin, bluish smoke. The blue smoke is from the charcoal itself starting to burn.

35. When the thin blue smoke is issuing from all 4 steam vents on the lid or from all 4 chimneys if reverse draught has been applied, the pyrolysis phase is complete and the kiln can be shut down and allowed to cool.
36. Thoroughly seal up all air inlets and any remaining gaps at the base of the kiln with sand/soil.
37. Thoroughly seal up the lid perimeter with sand/soil.
38. Cover all 4 steam vents in the lid with blocks and seal with sand/soil.
39. Remove the chimneys and cover or bung up the chimney fittings in the air inlet/outlet channels.
40. The kiln can take between 6 and 12 hours to cool before the walls can be touched and the lid removed safely. It may take 24 hours before the kiln is completely cold.

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## Emptying the kiln

41. Lift the lid off.
42. Remove the kiln body by lifting up one side and then rolling it away to leave the finished carbonized charge behind.
43. If parts of the charge are still hot douse with water.
44. Sort out incompletely charred wood from charcoal – the latter is lightweight, black all the way through, and will break up easily; while the incompletely charred wood (usually from the top and sides of the kiln) is heavier, looks like brown wood, and can’t be broken when struck.
45. Sieve the rest of the charcoal to separate reasonable sized pieces from the very fine charcoal and ash concentrated at the bottom of the kiln.

## Common Misconceptions

"*Wood must be well seasoned to make charcoal.*"

- It is preferable to use seasoned wood but it is still possible to make charcoal from freshly cut wood. The much greater moisture content takes longer to be driven off and takes more heat requiring more wood to be fully burnt at the bottom of the kiln, and so the yield will be lower. It is also more difficult to achieve the temperature for carbonization to take place properly.

"*Cutting the wood into short pieces will help the carbonization process.*"

- Cutting the wood into shorter pieces speeds up the seasoning or air-drying of wood. This can result in a lower moisture content which in turn will help the carbonization process.

Water moves through wood 10-15× faster along the grain than across it. If bark is left on, evaporation of moisture radially is half that of a debarked log. The speed of drying is therefore largely determined by the length when the length is less than 10-15× the diameter.

If wood is to be made into charcoal a few weeks to a few months after felling cutting into shorter pieces immediately after felling will speed up air drying leading to lower moisture content by the time the kiln is loaded. Priority should be given to cutting the larger diameter logs into shorter pieces since these inherently take longer to dry. Moisture content can be reduced to the fibre saturation point in this time frame.

If the wood still has substantial moisture content when loaded into the kiln, then cutting into shorter pieces may speed up the removal of this moisture content during the initial phase of the burn. This may reduce the risk of partially carbonized pieces but won't improve the overall yield.

Once the wood is dry, however, pyrolysis proceeds at a similar rate in any direction, so unless the logs are very short, e.g. similar in length to their diameter, the pyrolysis time is a function of the diameter. Hence, pieces of larger than average diameter should be cut so they can be placed in the hotter central part of the kiln.

"*Packing the kiln as densely as possible reduces the amount of air in the kiln, so reducing the amount of charcoal burning away to nothing.*"

- The main thing that packing a kiln densely does is to maximize the amount of wood in the kiln and thus the yield for a given run. Packing a kiln too densely, though, especially a small one tends to restrict the early flow of exhaust gases through the charge, making it more difficult to reach and maintain the necessary carbonization temperature. The volume of air in the kiln initially is insignificant compared to the volumes of air feeding in and exhaust gases vented during the whole process. Irrespective of initial packing the charge in the kiln tends to collapse during carbonization to a similar consistency.

"*The lid must be in place at the start to stop the whole wood charge from catching fire which would unnecessarily reduce the amount of charcoal produced.*"

- The lid is best left off a small kiln so as to speed up the initial heating up of the kiln. Once hot enough the wood at the top of the charge may light; this will further speed up the heating of the kiln. Only once the kiln has reached the sufficient temperature for carbonization should the lid be put on.

"*Once an initial burn has taken place to heat and dry out the wood all air supply must be blocked, otherwise the charcoal will burn away to nothing.*"

- At the temperatures required for carbonization a kiln loses heat through radiation and convection at a considerable rate, and so the air supply must be kept open for a limited burn to maintain the kiln at these temperatures. Only a fraction of the wood charge is sacrificed by burning.

"*Steam, which is from the moisture content of the wood, is only vented from the kiln during the early part of the carbonization process.*"

- The removal of moisture, although predominantly occurring at the beginning, continues throughout the carbonization process as moisture is removed from the middle of the largest diameter pieces of wood. Water in the form of steam is also one of the volatile products of the pyrolysis reactions.

"*Restricting the release vents will help keep the heat in.*"

- Actually restricting the release vents will tend to slow down the carbonization process and slow the burn at the bottom. This in turn will reduce the temperature leading to the carbonization process slowing or even stopping. Opening up the bottom to allow more air can restore the burn and the overall temperature, but the kiln will tend to be too hot at the bottom resulting in a lot of small charcoal pieces and not hot enough at the top resulting in un-carbonized wood.

"*Wind blowing on the kiln will cool it down on that side.*"

- Actually wind will increase the flow of air through the air inlets on the side facing the wind increasing the burn rate and thus increasing the temperature on that side – this should be compensated for by restricting the air inlets on the windward side.

"*If I make sure the air inlets are sealed up, I can make the kiln start to cool down, even if some of the outlets are still producing smoke.*"

- Towards the end of the process sealing up the air inlets alone may be insufficient to shut down the carbonization, partly because exhaust will tend to draw air in through the smallest crack, and partly because as the wood fully dries out the process becomes increasingly exothermic maintaining the temperature for the pyrolysis reactions without the need for burning with air.

"*The process of carbonization will continue for a while until the kiln cools down after shutting off all the outlets to the kiln.*"

- Carbonization depends on the release of the volatile products of pyrolysis reactions; if these are prevented from being vented from the kiln the concentrations of them will build up rapidly in the kiln and inhibit further reaction.

## *Effect of Kiln Size on Operation*

It is a general fact that processes in nature and engineering work differently at different scales, and this is true for charcoal kiln operation. The standard metal kiln design has a diameter of 2.1-2.4m. The kiln at Parndon Wood is a scaled down version with a diameter of only 1.2m. There are significant differences in operation, in particular the typical time for carbonization. Charcoal can also be made in a much smaller container still such as a 200 litre oil drum, which is different again in operation. The size and carbonization time for various kilns are shown in Table 1 below.

**Table 1 Kiln size and burn time**

| | Size | Volume | Surface Area | Max rec timber dia | typical pyrolysis time | cooling time |
|---|---|---|---|---|---|---|
| Standard metal kiln | ∅=2.3m<br>h=1.7m | $7.7m^3$ | $16.758m^2$ | 300mm | 16-24h | 16-24h |
| Mini metal kiln | ∅=1.2m<br>h=1.2m | $1.425m^3$ | $5.705m^2$ | 150mm | 5-8h | 12h |
| Oil drum | ∅=0.507m<br>h=1.014m | $0.204m^3$ | $1.817m^2$ | 50mm | 2-3h | 3h |

## Rate of Carbonization

The differences are accounted for by how heat loss from the kiln and heat generated in the burn vary with size. The rate of heat loss through convection and radiation for the same kiln temperature is proportional to the surface area of the kiln. There is further heat loss due to exhaust gases being vented. This can be assumed to be roughly a constant fraction of the heat generated, although a small kiln is probably less efficient than a larger one.

The potential chemical reaction rate and consequent rate of heat generation for similar material is proportional to the volume of wood. Actually it is proportional to the total surface area of the wood, so the potential rate of heat generation per unit volume is approximately inversely proportional to average log diameter. Generally the aim would be to use smaller diameter logs in a smaller kiln.

The rate of heat generated can, however, be varied: it can be reduced by reducing the pyrolysis rate by restricting the exhaust flow; and it can be increased by increasing the amount of material undergoing complete combustion by increasing the air supply.

For a constant kiln temperature the rate of heat loss is matched by the overall rate of heat generation. As kiln dimensions are increased the surface area and hence heat losses for a given shape increase with the square of linear dimensions. However, the volume and hence for similar material the heat generation potential increases with the cube of linear dimensions. Consequently for a larger kiln the rate of pyrolysis and/or combustion needs to be restricted.

The total heat energy produced during the whole carbonization process for a given ratio of pyrolysis to combustion will be proportional to the mass of the wood charge. For similar material and filling strategy this mass is proportional to the volume of the kiln. The total time for carbonization is equal to the total heat energy generated ($\approx\propto$ volume) divided by the rate of overall heat generation equal to the rate of heat loss ($\approx\propto$ area). As a result the total carbonization time is very approximately proportional to volume/area and hence increases with linear dimension.

If the rate of the pyrolysis is reduced and the rate of combustion increased to compensate, i.e. the ratio of combustion to pyrolysis is increased, the total heat energy released and the carbonization time can be increased. This might be desirable to ensure larger diameter logs can be carbonized right through. Slower pyrolysis may also produce a higher yield. If larger diameter logs are used the net density of the wood charge may be greater, leading to a greater carbonization time.

## Cooling Rate

For a given kiln temperature the heat energy contained in the finished hot carbonized wood is proportional to the mass of charcoal in the kiln. For the same yield efficiency this mass is a fraction of the mass of the wood charge which is approximately proportional to the kiln volume.

The rate of heat loss at any temperature during the cooling phase is proportional to the surface area of the kiln.

The time taken for the kiln to cool down is equal to the integral over the temperature drop of the heat energy capacity of the hot charcoal divided by the instantaneous rate of heat loss. Cooling time is therefore approximately proportional to the volume divided by the surface area of the kiln and hence for the same shape varies with linear dimension.

# *Scientific Background*

## Wood Composition

Wood in addition to its moisture content is composed of cellulose, hemicellulose, and lignin, plus small amounts of extractives, i.e. resin, and minerals (which produce ash when the wood is burnt). Cellulose and hemicellulose are carbohydrates similar to sugars because they are effectively compounds of carbon (C) and water ($H_2O$). The chemical composition and percentages in wood of the first three are given in Table 2 below:

**Table 2 Wood Composition**

| | Chemical formula | Hardwood mass % | Softwood mass % |
|---|---|---|---|
| Cellulose | $(C_6H_{10}O_5)_n$ | 43% | 43% |
| Hemicellulose | $(C_5H_8O_4)_n$ | 34% | 28% |
| Lignin | $[(C_9H_{10}O_3)(CH_3O)_{0.9\text{-}1.7}]_n$ | 23% | 29% |

The atomic masses can be taken to be: carbon, C=12; hydrogen, H=1; and oxygen, O=16. From the chemical formulae of the compounds and the atomic masses the percentage mass of each element in the wood can be calculated as approximately: $C\approx50\%$, $H\approx6\%$, $O\approx44\%$.

## Moisture Content

All wood for practical purposes contains some moisture content. The majority is so called “free water” contained in the cell cavities which can evaporate fairly easily. The rest called “bound water” is much more tightly bound within cell walls and takes much longer to evaporate. The point during drying at which all free water has evaporated but the bound water has yet to do so is called the fibre saturation point. The fibre saturation point is the point at which shrinkage of the wood starts to occur. The moisture content is still chemically water, i.e. $H_2O$; it is distinct from any hydrogen and oxygen chemically bound with carbon in the wood compounds. Moisture content can be quoted on a wet or dry basis, i.e. the mass of water as a percentage of the mass of wet wood or the mass of the wood when fully dry, i.e. all moisture removed, respectively. Moisture content is usually quoted on a dry basis, so it can be more than 100%.

To convert between moisture content on dry basis, MC, and moisture content on wet basis, $MC_w$, use the following formulae:

$MC = MC_w/(1-MC_w)$

$MC_w=MC/(1+MC)$.

## Removal of Moisture Content

During carbonization the free water is driven off once the temperature reaches ≈110°C, while the bound water requires a temperature of ≈150°C.

The heat energy required to remove moisture from wood is the latent heat of evaporation, $h_{fg}$, for the relevant ambient temperature. At a typical outdoor temperature of 15°C this is 2613kJ/kg(water).

The energy used for moisture removal per unit dry mass of the wood is given by $MC\times h_{fg}$.

Burning wood involves chemical reactions producing carbon dioxide and water, for example for cellulose:

$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_20$

The calorific value of wood, $Z_d$, is the heat energy released by burning unit mass of dry (0%MC) wood. This is typically in the region 20000-22000kJ/kg.

The fraction of combustion energy used to evaporate the moisture content of wood when it is burnt, which is the same as the fraction of the wood charge which needs to be burnt to dry out the charge during carbonization, is given by:

$MC \times h_{fg}/Z_d$

Practical calorific values for wood may be quoted on a wet basis where:

$Z_{wet} = (Z_d - MC \times h_{fg})/(1+MC)$,

$Z_d = Z_{wet}(1+MC)+MC \times h_{fg}$.

Typical moisture contents and corresponding fractions of wood charge burnt are set out in Table 3 below:

**Table 3 Wood moisture content & evaporation energy**

| | MC (dry basis) | MC wet basis | fraction of wood charge to dry[1] | Energy required (per kg of dry wood) |
|---|---|---|---|---|
| green softwood (max) | 200% | 67% | 26% | 5226kJ/kg |
| green hardwood (max) | 100% | 50% | 13% | 2613kJ/kg |
| green wood (min) | 45% | 31% | 5.9% | 1176kJ/kg |
| fibre saturation point (typ.) | 28% | 22% | 3.7% | 732kJ/kg |
| air-dried wood (typical outdoor seasoned) | 20% | 17% | 2.6% | 522kJ/kg |

1. Calorific value 0%MC wood, 20000kJ/kg. Ambient temperature, 15°C.

## Pyrolysis

Once the temperature of the wood reaches about 250°C the pyrolysis reactions start, first with the hemicellulose breaking down, followed by the cellulose above 300°C, and then lignin above 320°C. The volatile products of pyrolysis include combustible gases carbon monoxide (CO), methane ($CH_4$), and hydrogen ($H_2$), plus carbon dioxide ($CO_2$) and steam ($H_2O$), together with smaller quantities of other hydrocarbons, oils, tars, acetic acid, and methanol.

At the lower at of the temperature range for pyrolysis, around 300°C, the pyrolysis tends to be incomplete, resulting in a higher yield of low quality impure charcoal. The proportion of carbon in the wood retained is higher, but only a fraction of this is pure carbon with the majority still in un-decomposed wood compounds or in partial breakdown products with low volatility such as oils and tars.

As the temperature is increased towards 400°C more complete pyrolysis occurs resulting in a lower charcoal yield and proportion of wood carbon retained, but the charcoal becomes mostly pure carbon. This is probably because the lower volatility breakdown products can evaporate at the higher temperature or possibly breakdown further.

## Yield and Conversion Efficiency

The proportion of the carbon content of the wood which is converted to charcoal can be termed the carbon conversion efficiency. The yield is defined as the ratio of the mass of charcoal produced to the dry mass of the wood charge. If the carbon conversion efficiency is 100%, the yield equals the proportion of carbon in dry wood, i.e. ≈50%.

The main chemical reaction and energy release in burning charcoal is:

$C + O_2 \rightarrow CO_2$ + 393500kJ/kmol.

The atomic mass of carbon is 12kg/kmol so the energy released = 32792kJ/kg.

This is very close to measured calorific values of charcoal which are in the range 29770-33200kJ/kg. It is also similar to fossil coal at 30MJ/kg.

The ratio of the energy available from burning the charcoal produced to the energy from the wood charge if it had been burnt directly is termed the energy yield.

If 100% of the carbon content of the wood could be converted to charcoal (e.g. for the cellulose component: $C_6H_{10}O_5 \rightarrow 6C + 5H_2O$), the energy available from burning the charcoal produced per unit dry mass of original wood would be given by:

32792kJ/kg × fraction of carbon in original wood = 32792kJ/kg×50% = 16396kJ/kg.

For a calorific value of the original wood of 20000kJ/kg, the theoretical maximum efficiency of energy conversion is 16396/20000 = 82%. In this case the energy difference of 20000–16396 = 3604kJ/kg is most likely released in the form of heat, making the reaction exothermic once the moisture has evaporated.

In practice charcoal production never reaches 100% carbon conversion and consequently yield and energy conversion figures are proportionately less as shown in Table 4 below.

**Table 4 Carbonization Efficiency**

| | Carbon conversion efficiency | Yield | Energy yield |
|---|---:|---:|---:|
| theoretical | 100% | 50% | 82% |
| retorts with waste recovery | 73-85% | 37-43% | 60-70% |
| high efficiency kiln | 66% | 33% | 54% |
| metal kiln | 27% | 13% | 22% |

The additional energy difference is accounted for by practical radiation and convection heat losses from the kiln and the calorific value of the combustible volatile products of carbonization vented from the kiln.

## Torrefaction

If the temperature of the wood only reaches about 250°C, only partial carbonization will occur. The moisture content will be removed but pyrolysis will be quite limited. This process is termed torrefaction, and the result is called torrefied wood. The mass yield is considerably higher than when making charcoal, as is the energy yield. However, the calorific value of torrefied wood is much lower than that of charcoal, being only slightly higher than that of 0%MC wood.

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