Wood as fuel: from cooking to electrical energy

A chapter in: *Trees of the people*, by Alan R. Walker
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In the lands where our ancestors evolved fire was a common event. The tropical climate induced towering clouds as the rainy seasons approached. Thunder rumbled through the night whilst lightning flashed between clouds and crashed down on isolated trees. Grass and bush flamed as turbulent air spread the fire-front across the plain. Animals died: antelope, hares, insects. Their corpses, half roasted, were eagerly sought by our ancestors and other scavengers as easy pickings of soft tasty food. Some people helped the flames along using fire-sticks, as smouldering brands, to ignite areas harbouring suitable prey. So the people discovered how to use fire as they added fire-sticks to their toolkit of digging sticks and cutting blades manufactured from chert, obsidian and flint.

Firewood burning in a fire-pit hearth. Credit: Wikimedia, Jon Sullivan.

Then, during some long time of trial and error with fire, people worked out how to maintain a constant flame from collected woody material: dry leaves as tinder and dead-wood sticks and broken branches. Warmth and light attracted people together during the long dark cool evenings, then, as most of them slept on ground close to the fire, their sentinels kept the flames alive to deter hyenas and other fearsome things of the night. Knowing the good taste and easy eating of fire-trapped animals and of plant tubers, people began to maintain hearths for cooking by simple roasting.

Evidence for origins of use of fire.

Hearths are the earliest archaeological evidence of human use of fire for cooking. Bowl shaped hearths with soil baked to 800°C, with traces of charred wood at these hearths – sparse evidence but dating from 1.7 to 0.2 million years ago, in the times of *Homo erectus*. Onward through time, some *Homo sapiens* in Africa left flint blades near hearths, with the flint showing damage from fire. From about 125,000 years ago there is widespread evidence of anatomically modern humans controlling fire for various practical purposes.

Blazing charcoal with forced air flow into a forge: 1260°C can be reached, sufficient to melt iron. Credit: Wikimedia.

As primates we humans are stranger than our pride will admit. We are weird, zoologically speaking. Compared to our primate relatives we have small mouths with small teeth, small jaw bones, and small masseter and other muscles of mastication for chewing our food. Our gut is too short for fully digesting raw plant food and our canine teeth are too small for tearing lumps of raw meat off a carcass. Nevertheless, we are the most formidable predators of all land animals. In Africa we evolved with multiple new competencies, including the ability to work together as pack hunters. We spoke and gestured to pass detailed information between the group. We ran slowly and persistently, hour after hour, as we tracked the spoor of prey such as large antelopes. As we ran upright the high tropical sun on our sweat-cooled skin stressed us less than our prey. Eventually the prey collapsed exhausted and suffering from acute hyperthermia. By the time our ancestors spread into the cold northern lands they were adapted intellectually to the complex social work of hunting mammoths for the meat, also the skins and the bones for constructing housing. From where did that prodigious energy come from for persistence hunting over tropical savannas, or for ranging far out over tundra in search of mammoths to kill? How did these people gain enough metabolic reserves for their legs and their big complex brains to work so long and so hard?

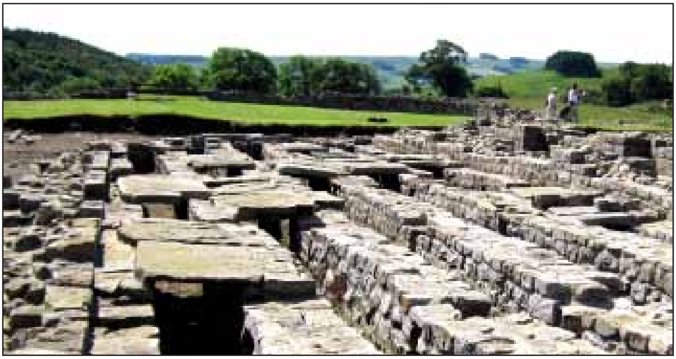
For us now it is difficult to be sure how our life worked that long ago, but cooked food is the simplest answer for this ample supply of energy. Indirect evidence for a hypothesis about cooking in human evolution is our inability to do more than barely survive on raw food. Food that is both raw and not processed and refined by modern techniques is inadequate for functional human health as defined by ability to reproduce and maintain a local population. Cooking of plant and animal food is a human universal. All peoples and their societies studied everywhere by anthropologists cook most of their food. Cooking tubers, grains, leaves, meat, eggs . . . increases their digestibility and thus their available energy for our specialized guts. Some raw foods such as ripe sweet fruits, honey, liver, bone marrow, and brain can yield ample energy but they are rarely available in sufficient quantity or regularity.

Family in Tanzania returning from firewood gathering. Credit: Wikimedia.

Too cook we gathered firewood and maintained our fires. We became unique amongst the entire living world. Other animals use tools. Spiders spin their webs, birds gather materials to construct their nests, and chimpanzees crack open nuts with rock hammers. Many other animals exploit the smouldering remains of a bush-fire to supplement their diet.

We however invented the technology that transformed our hand-tools, our knives and axes, into what would eventually become the revolution of externally powered industrialization. We invented hand-axes, we invented cooking, and then we started cutting down trees with anything from a hand-saw to a fifteen tonne semi-robotic harvester machine burning diesel oil refined from the deeply buried fossils of ancient trees. We came to depend totally on external fuel. As a gambit in the evolution of life-forms this uniquely specialized dependency on external fuel bears potent dangers.

Invention of metal tools, cement and glass.
We invented metal tools as variously we observed gleaming molten metals oozing from the lumps of rocky material we used to build hearths. At first copper was more useful for manufacture of simple vessels and showy, shiny, ornaments. The discovery of adding a small proportion of tin to the melting copper transformed metallurgy into a tool-making business. Hand-axes made of this harder alloy bronze could be used to chop down trees then fashion the wood into tools, furniture and houses.


Remains of a Roman villa in England showing hypocaust supports and flagstone flooring.

Burning wood for its values of sociability and comfort expanded as we discovered how to provide sufficient fuelwood by coppicing trees. The habits of wealthy people of the Roman Empire who colonized the cold lands of northern Europe, up to about 1570 years ago, remain in clear view. These are the underfloor heating systems, hypocausts, commonly installed for grand villas built of stone blocks. Furnaces fed hot air between stone supports of the flagstone floors. A recent experiment at a well preserved example in Germany demonstrated the fuel consumption for this luxury: 130 kilograms of wood per hour to heat one villa. Communal hot baths were popular and provided to boost the morale of soldiers stationed nearby. Fireplaces for heating or for the kitchens of palaces and castles, built in later centuries, were similarly extravagant in size and fuel consumption.

Cooking fire-place in the remains of a royal pleasure palace of year ~1620 in Scotland. The stone arch is 1.8 metres high.

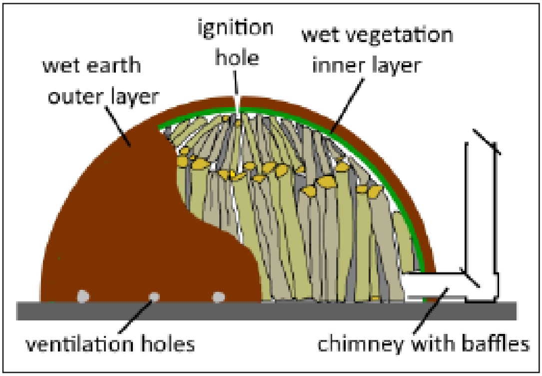
Lime mortar for holding these stone blocks together or making concrete required massive kilns to roast crushed limestone rocks. When originally fired with wood a typical kiln needed 720 kilograms of wood per day. Ceramic materials as bricks, tiles, and glass, required great heat to transform the raw materials of clay or quartz sand. To melt these rocky materials required temperatures of at least 1575^{o}C. In turn, to reach that heat required air forced from bellows onto the fuelwood and venting of the exhaust gases up through tall chimneys. Smelting of iron from its ore required similar furnaces and temperatures. Quantities of fuel needed for all this industry grew rapidly to meet the demand for lime, brick, glass and iron. A forge to smelt iron-ore needed about two tonnes (dry weight) of fuelwood for one tonne of finished iron.

Metal smelting must have developed as interaction with the discovery of charcoal which originated as partly burnt wood at margins of primitive forges. Charcoal production developed to a form that now remains widespread and common: the earth-mound charcoal kilns operating together with modern versions made of iron and concrete. Stem wood is stacked then covered with branches and earth to keep out most air whilst some air-flow is controlled through vents. When lit, partial combustion of the wood heats it sufficiently to drive off volatile components. Remaining are lumps and rods of black, porous, material that is ninety percent carbon. Charcoal is light, dry and waterproof, and when lit this consistent fuel burns slowly and is easy to control. On a simple cookstove little smoke or ash is produced and with forced supply of air charcoal burns intensely hot.

Ten stone kilns built in 1877, each 7.5m tall, formerly to supply charcoal for metal smelters in Panamint Valley, California. Pinyon pine and juniper woodlands on surrounding hills supplied the wood. Credit: Wikimedia.

Smoke from a charcoal kiln in Slovenia at 1949. Credit: Wikimedia

Colonizing armies of Romans needed to manufacture, on site in their new territories, tools and weapons of iron. In the Weald area of southern England where sandstone rock strata contained good deposits of iron-ore, the numerous military iron-works produced an estimated 540 tonnes of iron over a period of 120 years. A further calculation was that this needed charcoal from coppice woodland covering 9300 hectares. Coppiced oak woods for that purpose were managed for sustainable yield during a span of time measured by the century. Thus these invaluable woodlands remained widespread then and they remain there now, although much diminished in area by expanding croplands, housing estates, factories and roads.



Construction of a traditional charcoal kiln, also fitted with a ventilating chimney.

Modern metal charcoal kiln for small scale domestic use.

As the demand for iron grew rapidly in the early days of the industrial revolution coal became substituted for fuelwood for general heating and to produce industrial steam. For iron-smelting raw coal was no use:

its oily volatiles contaminated the molten iron. Hence the invention of coke, produced from coal similarly to charcoal from wood. Coke-fired iron smelters roared faster and hotter, driving this revolution. So fossil fuel came to dominate industry and human labour. From one kilogram of coal there is available enough embodied energy as chemical bonds, to release as joules, the same amount that would power the hard physical labour of one human for three working days of eight hours each. We became dependent on our machines, we had to feed them constantly.

> Terminology of this topic is variable, here it is simplified. *Fuelwood* includes: firewood as sticks and branches for a cookstove; stem wood for manufacture of charcoal; woody waste as anything combustible from dry dung to forestry and construction wastes; timber specifically grown and harvested as stem wood for processing to burn for heat and electricity. Also wood for use as fuel must be dry. *Biomass* in this context includes all the above except charcoal. *Biofuel* usually means ethanol, diesel oil, and methane, made from plants or industrial waste, for burning in engines and generators.

Cooking with fuelwood.

Two billion people cook their daily food over fuelwood, as either firewood or charcoal. They do this more out of necessity than choice. Their natural resources of woodlands and fuelwood are almost as vital as their supply of water. In the countries and regions where fuelwood is commonly used fossil fuels may nominally be available but expensive or difficult to obtain. Also the necessary cookstoves for these fuels are more expensive or otherwise disliked. This is more than just a matter of simple poverty. Even when subsidized supply of electricity is available to low-cost social housing, fuelwood may remain the preferred option. During the fifty or so years this topic has been researched the widespread prediction that people's fuel use would ascend a technological energy-ladder (wood to kerosene to gas to electricity) has not held up.

The number of people in many less wealthy countries relying on woody fuel, from dried dung of cattle to charcoal, at year 2000 was estimated at 2.09 billion. The calculated trend to 2030 goes to 2.6 billion people. In these countries the population is calculated to increase by x1.4 and that increase in woody fuel is x1.25. A similar calculation for just India gave estimates for 1994 to 2015 of a population increase of x1.33 and of fuelwood use of x1.42. Thus any transition away from dung, firewood and charcoal is expected to be slow. The strongest brake is poverty. This is compounded by the complexities of formal land-rights which contrast with the informal socially organized access to woodland as a resource, as a commons.

Roadside charcoal sellers in Zambia. Credit: Wikimedia.

In regions where wood is substantially used as fuel for cooking forests, woods and plantations of suitable species of tree are managed to maintain a steady supply of timber for construction, and branchwood and brash for use as fuel. The extent to which this is done, in terms of hectares of sustainable forestry per region, or proportion of fuel wood and charcoal produced sustainedly are difficult to generalize. The trend toward this favourable state of balance between new growth of trees and consumption of wood in this context has been formalized as: *Sustainable-wood theory of change*. This term is in deliberate contrast to the usual narrative about use of wood as fuel being merely a stage in a transition between use of primitive fuels to use of modern fuels. The advantage of fuelwood produced in sustainedly managed plantations and woodlots is that the carbon of the wood has recently been drawn down from the atmosphere by the leaves of the trees, stored there for several decades during the growth of the trees. Timber and other forest products can also be provided. In contrast, natural gas as methane from geological deposits, also kerosene refined from oil, are fossil fuels. These materials are essential for making plastics and technical materials such as lubricants. Burning methane or cooking with electricity generated by burning coal directly adds to rising concentrations of carbon dioxide in the atmosphere.

Charcoal traders supplying a city in Ghana. Credit: Wikimedia.

Electricity generated sustainedly, as hydroelectric systems for example, is technically the best for powering a cookstove, but so far is too expensive for many people. Fuelwood for cooking is indeed a dirty fuel, whether as wood or charcoal, but to denigrate it in favour of burning fossil fuels because that is more clean and modern may be an unproductive policy in the long term. The potential for sustainable forestry using indigenous and exotic species of trees in those regions of the world where cooking is mostly fueled by wood is described in 'Regeneration' chapter.

There has also been over the last fifty years an idea about these less wealthy countries that they have a fuelwood crisis. Many trees are being felled from natural forests. This is usually the well publicized felling for commercial and highly profitable timber exports. It is cause for much concern and action about how the world's natural resources are conserved and managed. Most simple gathering of firewood for domestic cooking and some heating is in a separate category for reasons of practicality, economics and access. Wood for large-scale commercial production of charcoal however, may come from natural forests despite legal sanctions against such felling.

Stock of firewood for sale within this settlement. Credit: Wikimedia, Francisco Anzola.

This situation is complex and difficult to generalize, and much has changed over these fifty years. People in need of fuelwood increasingly obtain it from woodlots grown for that purpose in small patches, pockets of land unsuitable for food crops and rows of trees that double up as boundary lines and shelter belts against wind and soil erosion. These woods are planted and managed for fuelwood, for small timber, and for leafy browse for cattle and goats. *Eucalyptus* species are often preferred (but not for leafy browse!). This hardwood is effective for construction and has good qualities as firewood or for manufacture of charcoal. The trees grow fast, can coppice well, and are by evolutionary chance adapted well to regions far from their indigenous home of Australia. *Eucalyptus globulus* was introduced to highland regions of Ethiopia in 1895. Hundreds of thousands of hectares of this utilitarian tree species have been planted and maintained for fuelwood and timber. The annual increase in planted area continues, also there is scope for incorporation of indigenous tree species of *Juniperus*, *Podocarpus* and *Olea*.

Simple cookstove of 3-stone design but formed with clay. Credit: Wikimedia, Otuo-Akyampong Boakye.

Experimental design of metal cookstove being tested in Sudan. Credit: Wikimedia, Laura Toledano.

Improved design of cookstove made of cement with chimney to exterior at left. Credit: Wikimedia, Pooja Jadhav.

Tree planting in the adjacent country Kenya is another well studied example of this trend. Here the *Green Belt Movement* was started by Wangari Maathai in 1977. By 2004 her achievements were recognized by award of the Nobel Peace Prize. Her memory and example now inspire the planting of many millions of trees in Kenya and elsewhere, mainly by women empowered by the Movement and trained in arboriculture, forestry and related trades. The aim, in terms of forestry economics, is to establish a much greater stock of trees available to ordinary people who then obtain their supply of cooking fuel from the annual sustainable yields of that expanding stock. Although timber felling in the large natural forests of Kenya, mostly state owned and managed, continues unsustainedly the situation for woodlands within agricultural land steadily improves. A survey using data from satellites and from field surveys of 10 million hectares in the twenty percent of Kenya of high agricultural potential and where eighty percent of Kenyans live, revealed an annual increase of planted hectares between 1986 to 1992 of 4.7 percent. The dominant trees were *Eucalyptus* species, mostly in small plots where the people had adequate land-tenure and rights. (This land-use is easily visible using Google Earth or Bing Maps: follow a transect at high magnification going north east from Nairobi to Nyeri, or Naivasha to Nanyuki.)

Wood fueled cook-stove, and a heating stove. These contribute to reduction of CO_2 emissions if substituting for fossil fuels. Credit: Wikimedia, Thomas Quine.

This widely publicized example from one nation in eastern Africa makes tree management for fuelwood appear straightforward, but at a global scale there are many examples of contrary and deep-rooted blockages to improved supplies of fuelwood from local woodlots. This topic is mostly beyond the scope of this book, nevertheless some of the sociological and economic factors are too important to neglect. Wangari Maathai's campaign empowered women within the context of improved schools, starting with partly subsidized primary schooling for girls and boys, and continuing with easier access to medical care and family planning. Also the formal legal system was aligned sufficiently with traditional norms of land rights that small-holder farmers gained the confidence to plant a crop – trees – that would take decades to become fully useful. In other countries, and with particular peoples within them, there occur problems such as a cultural aversion to forests as places to fear, places with many imagined and some real dangers. In contrast, trees are often thought of as a natural resource that exists for us merely to extract, not to plant, nurture and harvest. When nomadic pastoralists need to settle and grow things their first crops will be cereal plants – trees will come later. At the broader level of institutional management of resources the work of forestry is up against several problems. Administrators are likely to consider fuelwood as primitive, destructive, and unhealthy. Traditionally, forestry as a profession has operated in a top-down, government sponsored style, operating at the scale of forests, not woodlots on agricultural land. The work of forestry departments in many regions has been focussed on preserving national forests against poachers and illegal felling, not on provision of fuelwood. Thus improvements of the basic resource of woodlots managed for fuelwood come slowly and need detailed understanding of the social norms and economic constraints of many separate communities and cultures.

Small fuelwood as mixed hardwoods from a community managed forest in France.

Domestic fuelwood supply for heating, Czech Republic. Credit: Wikimedia.

Charcoal trade.
People living in towns and cities of less wealthy countries rely on charcoal for cooking if they cannot afford kerosene or gas (usually as bottled liquefied natural gas, which is methane, or petroleum gas, which is propane). Trade in charcoal is a large and active business, much of it in the informal sector (not run by incorporated companies). There are series or chains of small traders who cut the wood, who operate the kilns, who transport into town markets or sell charcoal directly by the roadside. The trades are important sources of income for a wide variety of people in these chains. They meet either their own needs on-farm, or the demand from a large market of people in towns and cities who can afford only this fuel. An estimate of charcoal annual use and cost per household in South Africa in 2004 was 4343 kg at a cost of US$ 311. At about the same time in Kenya consumption of charcoal was estimated at 350 to 600 kg per household, and in that country two million people were economically dependent on production and trading of charcoal. Then the population of Kenya numbered about thirty five million.

The scale, economics, and techniques of production of charcoal varies. One kiln may be supplied by the wood harvested on one farm, with surplus charcoal sold to supplement income. Collectives of kiln operators may source their wood from a state-owned forest that is managed sustainedly, then transport the charcoal to city markets on trucks. Nevertheless the threat to forests from illegal felling to meet this massive demand is often present. The need for sustainable supplies of fuelwood for charcoal can be paired with more efficient methods of converting wood to charcoal. A kiln is intrinsically wasteful: depending on the design about 10 to 40 percent conversion from fully dried wood to charcoal. Improvements in design, usually of more efficient inflow of air and venting of exhaust gas both increase yield and reduce pollution.

Smoke pollution and improved cookstoves.
The smoke issuing from a charcoal kiln is huge and foul, but at least it rapidly disperses away from most people. Using a cookstove without a chimney, burning firewood in a small poorly ventilated kitchen area, is a potent hazard to the health of the cook and everyone else in the house. Woodsmoke is smoky from its particulates: microscopic pieces of unburnt woody material with coatings of various tars, similar to smoke from tobacco. Invisible are the gases: carbon monoxide, ammonia, nitrogen oxides, and so on. The fine dusty ash contains caustic alkalis. Poor health caused directly by domestic wood smoke includes increased vulnerability to infections of the lower respiratory tract and lungs, leading mainly to pneumonia, also chronic obstructive pulmonary disease. The World Health Organisation specifies a health limit for particulates of 40 micrograms per cubic metre of air, but cooks working over fuelwood cookstoves may be exposed to between 300 to 3000 micrograms. Typical size of this particulate matter defined as seriously dangerous is measured in micrometres (1 thousandth of a millimetre) such as PM2.5 for particles of approximately 2.5 micrometres diameter.

Such indoor pollution, measured in terms known as disability adjusted life years (DALY, a measure of reduction of healthy life-span) is the fifth highest in a global ranking of health risks, at 33 million DALYs. That is greater than loss of health from malaria and from tuberculosis.

As with charcoal kilns, there is much scope for improving design of cookstoves to reduce both pollution and quantity of fuel required. A chimney to the exterior is the obvious improvement if possible, not only reducing smoke but inducing a steady flow of air into the base of the stove that can be controlled to give a hotter and cleaner combustion.

Cooking is often a conservative skill, constrained by time, money, and culture. Any attempt to introduce an improved design with the motive of improving health of both people and woodlands is likely to meet scepticism or simple inability to pay for some new-fangled contraption.

The simplest type of fuelwood cookstove, the arrangement of three large stones around a small fire-pit, used in a partially enclosed kitchen without a chimney will inevitably pollute the air that the cook and other family members breath. The more efficiently the fire can burn, the less smoke there will be. Efficient combustion depends much on the flow of air to the bed of the fire, then away from it in the hot plume of exhaust. Many people have experimented with improvements to simple cookstove constructed of ceramic or metal materials. The most effective improvement is a chimney of some kind. This will greatly improve airflow to the fire and potentially carry away smoke from the kitchen.

Many studies of the technicalities for improving such cookstoves are available. Some are more plausible than others because the deployment of these new designs to the people who need them must fit with the ability of the people to purchase and maintain them. For example, a design that incorporates an electrically powered fan to improve airflow to the fire, with power supplied by a heat-to-electricity device (thermo-electric generator) attached to the cooker, is unlikely to be affordable for people who are forced by poverty to cook using wood as fuel. (Fan assisted cookstoves are distinct from the fan that may sit on top of a domestic wood burning heating-stove to circulate hot air.)

> Efficiency and particulate matter from types of cookstoves. Data from Hakizimana *et al*. 2020.
> * 3-stone fire: efficiency 8-12%; particulates / cubic metre 2,800ppm.
> * Basic cookstove: efficiency 20-25%; particulates 1,700ppm.
> * Improved cookstove: efficiency 25-35%; particulates < 1000ppm.
> * Electric or gas cookstove: efficiency >35%; particulates <250ppm.

An advance in the use of woody material as fuel for various purposes – cooking, heating, generation of electricity – is the technique and use of pelleted biomass. The style and sheer heat during the operation of a domestic heating stove fueled with wood pellets is impressive. What seems to be a small amount of fuel delivered in small increments delivers concentrated and uniform heat. The same principal is done at massive industrial scale for providing heat to large blocks of domestic housing, or to run a large electricity generator. If the similar techniques can be adapted for small scale use as cookstoves that could be an advance on the usual options for improved stoves.

> Particulate matter as grams per amount of energy, as joules, delivered for types of cookstoves. Data from Mawuzi *et al*. 2023.
> * 0.256 ± 0.166 g/MJ of energy delivered for wood stove.
> * 0.043 ± 0.040 g/MJ of energy delivered for charcoal stove.
> * 0.041 ± 0.023 g/MJ of energy delivered for pellet stove.

Burning wood to produce electrical energy.
An intriguing possibility is emerging that people cooking their food with methods at the lower rungs of the so-called energy ladder could jump, could leap-frog, up to the top level of using electric cookers. Not only that, also with the electricity derived from renewable resources including much woody fuel burnt instead of coal, oil or gas. Such a trend would emulate the way mobile telephones, cell-phones, in many countries have enabled a huge expansion of spoken and text communications for trade, for banking, and for sociable information.

The wider story starts with enormous quantities of waste woody material from forestry and wood construction and manufacture. This potential waste can however be used as recycled wood products such as sheet materials made of woody particles, fibres, and chips. Alternatively, and specially for waste containing bark, leaves and woody construction off-cuts, electrical power stations can be fueled entirely with these wastes. For ease of handling, transport, and efficient combustion it is pellets that are fed into the furnaces to produce the steam that drives the turbine generators. Pellets of the same sort that are available in hardware stores for burning in domestic heating stoves. Now rapidly developing are systems and incentives to use these wastes and to grow fuelwood specifically for electrical power stations. The incentives and subsidies derive from political commitment to reduce emissions of carbon dioxide as a greenhouse gas and thus reduce risks of global heating. As introduced in 'Carbon', if a portion of woody material from a forest is used to provide energy in a way that substitutes directly for the use of coal, oil or natural gas then the carbon dioxide from the combustion of that wood has, during the last forty years or so of growth been drawn in from the air by the leaves of those trees. This is a relatively closed cycle that will reduce global heating as it substitutes for, or displaces, fossil fuels.

An old sawmill in USA with associated processors and mounds of accumulated woody waste Credit: Wikimedia.

The quantities of waste wood for this are huge. An estimate for the large forest industry of Finland at 1997 was that fifty nine percent of woody material goes to building and other products and forty percent goes to produce useful energy as heat and electricity. The remainder goes to landfill and if that is managed correctly the carbon there will remain stored, sequestered, for decades. Another study for Europe as a whole in 2008 showed how forest resources there have been increasing for the last fifty years at an annual rate of roughly 238 million cubic metres of stem wood. From all these forests the total amount of waste wood, as toppings, brash or slash, and spindly stems, suitable to produce heat and electricity, is 84 million cubic metres. The annual total then was 187 million cubic metres, or 150 million tonnes, of unseasoned wood. From this can potentially be extracted 411 terawatt-hours of energy.

> *Energy* is the capacity for doing work; energy that can be recovered and used from a kilogram of dry wood burnt in an efficient furnace is about 10 megajoules. For comparison an adult human during a typical working day needs 10 to 15 megajoules. Conversion between the two standard units for energy is 1 kilowatt-hour = 3.60 megajoules. Energy available from electricity stations is normally stated in megawatt-hours. *Power* of an electricity station, its *rate* of doing work, is stated in megawatts or the big stations in gigawatts.

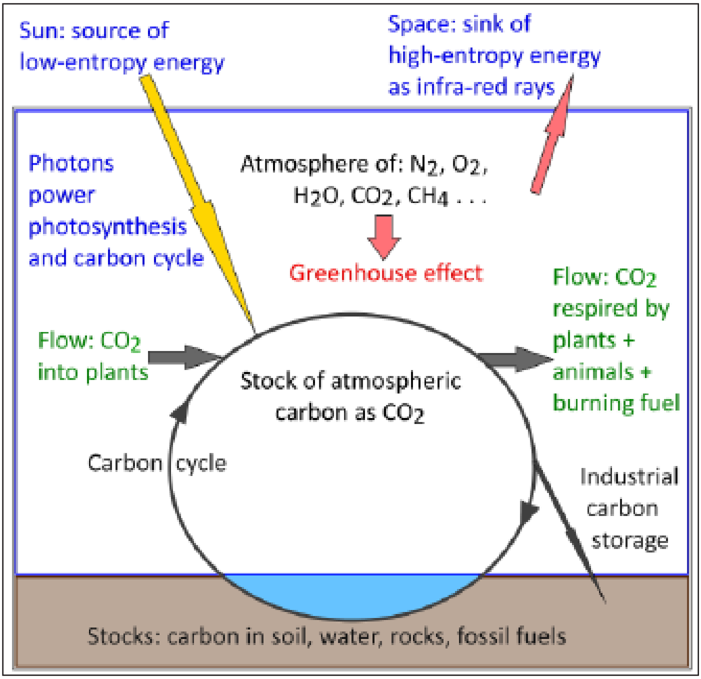
These forests are semi-natural or plantation, managed for sustainable production. Virgin, original, wild forest and woodland is rare and conserved in Europe – a land long ago densely occupied by people making use of trees. A study from the USA at 2002 estimated 63 million tonnes of waste wood generated from forest operations and this waste represented about twelve percent of total recoverable timber wood. Similar studies in Nigeria revealed for 2010 that quantities of wood waste including sawdust were 7 million tonnes each year, but that much of this was being dumped in landfill or burnt without recovery of useful energy. The problem with sawdust in landfill is that if exposed to air it may rapidly decompose to release methane, a greenhouse gas x25 more potent than carbon dioxide.

Controversy surrounds this trend of increasing use of woody fuels to provide heat and electricity. People argue that growing crops such as sugarcane to manufacture industrial ethanol as a fuel for motor vehicles carries serious danger of reducing agricultural land area for food crops. Alternately a factory extracting sugar as food may also use the large residues of sugar cane, the bagasse, to burn and generate electricity directly for the factory. Similarly large grasses such as miscanthus can be grown for fermentation into engine fuel or burnt to produce electricity, but again, should the land be used for food crops instead? This varied and complex topic is another one beyond the scope of this chapter.

Lynemouth power station, England; formerly coal fueled, then fueled with wood pellets. Credit: Wikimedia, D. Kuru.

Burning wood to reduce global heating.

The concept of biofuels, biomass as fuel, remains contentious and is now mixed up with the concept of bioenergy in the context of electrical power stations built next to sawmills and timber yards. If such power stations are fueled with woody material from virgin, native, forests or other forests not managed sustainedly there is a problem of consuming the *stock* of a resource (a forest) rather than consuming the *yield* of the stock (as harvested timber and waste wood). The yield must be sustained in the long term by simply planting more seedlings now than the number of mature trees felled in about forty years in the future. Or, in a semi-natural managed forest, the natural regeneration rate is assisted and monitored so that the stock remains and the permitted yield can be calculated. This yield of trees is equivalent to a slow, diffuse flow of carbon through the stock of carbon. As with water that flows into and out of a reservoir of drinking water.



Flow and balances of carbon and energy that influence the natural carbon cycle and include industrial storage of carbon. See next figure for quantities of carbon in a cycle like this.

To the controversy around biofuels is now added the complexity of various experimental methods to extract carbon dioxide from either the flue gases of these wood-burning electricity stations, or directly from the open air. The CO_2 captured then, as part of the system, is to be pumped for storage deep into rock formations, typically those that formerly contained oil or gas. Methods that can be adapted for this are already developed to drive out remaining reserves of these fossil fuels. The method applied at electricity stations coupled with wood burning furnaces is known as carbon capture and storage (CCS) and is planned to add to the potential for mitigating climate change. Not only planned but considered essential, not optional, if the targets set and agreed by the Paris Climate Conference of 2015 are to be met by stages in decades: 2030 to 2050. Thirty years are allotted to move toward a highly demanding target of stabilized concentration of carbon dioxide in the air and a rise in global temperature significantly less than 2°C above the pre-industrial baseline. Carbon capture, by any means other than growing more vegetation, is technically difficult and expensive for the equipment and consumes much energy. Currently this technology is more experimental than routinely operational.

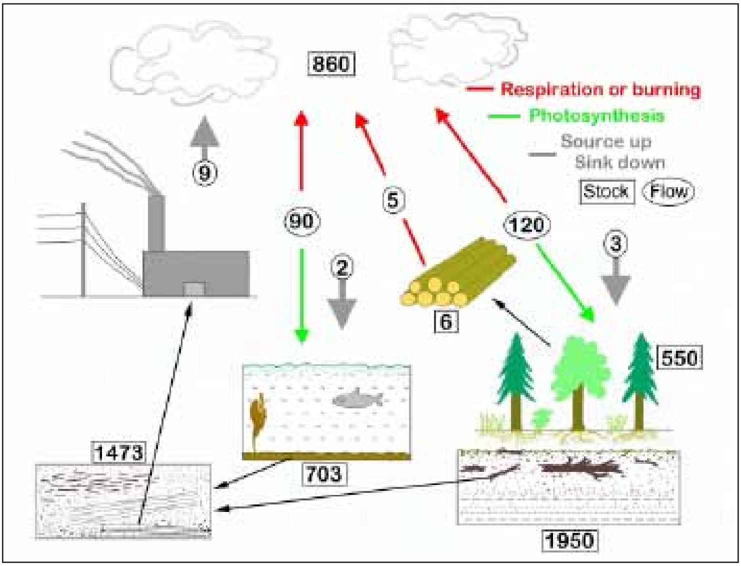


Figure from 'Carbon' chapter showing global carbon stocks and flows in billions of tonnes (GtC) during natural and industrial cycles. Stocks in *rectangles*, flows in *ovals*.

At the time of writing this, both the technique and the economics of increasing numbers of wood burning electricity stations are contentious. Current accounting procedures are problem enough at a technical level but they also operate in a political context of trading agreements for carbon emissions that are part of the mechanism for meeting the Paris 2015 targets. You may already have been offered the chance to buy, or found included as part of your ticket price, a carbon offset from an airline or even a clothing manufacturer. The trade is complicated, sometimes murky, but at best it is part of the balancing act needed to reach a point, target date 2050, known as *net-zero*.

Net-zero will be the balance point of carbon in against carbon out, hopefully reached in thirty years from time of writing. Also whilst the average increase in temperature of the air we breathe has risen from 1.1°C now to 1.5°C above the pre-industrial baseline. This temperature rise may seem inconsequential, but globally it represents a vast amount of additional energy churning our atmosphere into storms and disrupted weather, even before some of us start to submerge under rising seas. Carbon dioxide will flow into the atmosphere from our respiration and of nearly all other life forms, even trees. Apart from forester's harvester machines there will remain logging trucks and arable farmer's combine harvesters. A tradeable offset is available to a business that can demonstrate it has stored carbon in some way, usually indirectly by buying into the business of storing carbon in the form of planting, growing and harvesting trees. Net-zero is written into the core, the heart, of the internationally concerted work to avoid catastrophic levels of global heating. Changes in our behaviour to reduce greatly our own individual consumption of carbon energy are paramount.

Trees are important to assist this now and will increasingly remove and store carbon. Which brings this chapter straight back to that invention a million or so years ago of controlling fire for cooking. So fundamental was it that our evolutionary path was diverted from the simple life of our primate relatives to technological and intellectual life. Evolution proceeds by its independent dynamic, even if sometimes down a blind alley, into a no-through road. Now we work to make sure that our unique invention of cooking with fuelwood was a sign-post in a good direction.

continued

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