Chapter 27

Opportunities for technological transformations: from climate change to climate management?

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Note: Photos and biographies of co-authors can be found in the appendix.

The concept of carbon-negative products and a carbon-negative industry

We are still living, mentally and politically, in the ‘oil age’. Overall oil production, which secures mankind’s core requirements for energy and raw materials, sums up to about four billion tonnes of crude oil per year, equivalent to a cube with sides measuring four kilometres in length (official statistics of the US government, see IPM). Assuming a price of USD 100 per barrel, this translates into an economic value of USD 2.5 trillion. Crude oil, however, is running short already, and this will lead to further distribution conflicts, wars to control access to energy, economic depression, and poverty in the Third World. A reliable supply of oil is also a matter of existence for the chemical industry. Plastics, pharmaceuticals, and most objects we use in our daily lives would simply vanish without oil. The third, presumably most urgent issue associated with the oil economy is climate change and the protection of the atmosphere. As essentially all oil ends up sooner or later as CO_2 in the Earth system, an additional consequence of the oil economy is the generation of an excess 12.5 billion tonnes of CO_2 per year, with known and undisputed implications for the world’s climate.

This is a typical ‘dinosaur trap’: the individual facts are not questioned, but governments and industrial leaders propose only marginal changes to handle the inevitable. Reducing the discussion to a debate on ways to secure cheap and available energy or to open extra energy resources is too simple by far. The problem to be solved is the simultaneous optimization of the complex interactions between the production of energy, the consumption of raw materials, and the destabilization of our atmosphere. This obviously has to occur not on a national basis but on the world scale.

One of the typical ‘marginal’ solutions suggested by politics is to replace minor parts of the energy and raw material stream by biomass energy products. This includes, besides direct combustion, fermentation of carbohydrates to produce ethanol fuels, the cultivation of oil seeds (‘biodiesel’), or the generation of biogas via anaerobic digestion (Powlson *et al.,* 2005). The so-called first generation biofuel technologies are not unquestioned today: there are clear indications that, considering the whole supply chain, such measures may even harm more than they contribute to a solution (see Creutzig and Kammen, this volume). A detailed summary of analyses of the energy efficiencies, costs, and biological impact of such procedures was published by Gustavsson *et al.* as early as 1995 and was essentially confirmed in a new report published on behalf of the Association of the German Industry (McKinsey & Company, 2007). In the present context it is important to state that all types of biological fuel production schemes can at best only lower the further increase of CO_2, but cannot compensate for the already emitted CO_2 from fossil resources. This means that current biofuels do not help to solve the 'problem-triangle' of energy, resources and climate.

What would a really useful solution look like? It is obvious that evolutionary changes of current technology will not help us move out of this trap, but that technological transformations or technology leaps are urgently required. Systematic use of the sun for harvesting energy is certainly a transformation that could help to satisfy the energy demands of the world. However, this is not the focus of this essay. Instead, we will focus on describing how to achieve a carbon-negative energy system.

When considering climate change and the role of CO_2, it would be highly desirable not only to slow down further CO_2 emissions, but to reduce the total amount of CO_2 in the atmosphere. The idea is not only to provide a 'zero emission' energy system, but potentially to generate a new chemical 'CO_2 disposal' or CO_2-negative industry, i.e., an industry that allows CO_2 to be taken out of the atmosphere and deposited securely through chemical transformation into stable substances. This thought, as simple as it is, is only rarely brought up in discussions on global sustainability (Read, 2006). It means that the search for new and efficient carbon deposits has to be reiterated also from a chemistry point of view. Optimally, material benefits for society would emerge from the disposal of carbon by creating consumer products. This type of technological transformation is discussed in the present essay.

The most important carbon converter, which binds CO_2 from the atmosphere, is certainly biomass. A rough estimate of terrestrial biomass growth amounts to 118 billion tonnes per year, when calculated as dry matter (Lieth *et al.,* 1975, pp. 205–6; Bobleter, 1994). As biomass contains about 0.4 mass equivalents of carbon, removal of 8.5 % of the freshly produced biomass from the active geosystem would compensate for all CO_2 emissions from oil. Biomass, however, is just a short-term, temporary carbon sink, as microbial decomposition releases exactly the amount of CO_2 formerly bound in plant materials. To make biomass 'effective' as a carbon sink, the carbon in the biomass has to be fixed by 'low-tech' operations. Coal formation is obviously one of the natural conversion schemes that were active in the past on the largest scale. The sort of measure needed to protect the atmosphere is of a similar dimension: in principle, mankind has to re-create and speed up the transformation of plant material to coal, in other words, to create a new industry which converts about 10 % of the world's biomass into useful carbon products and deposits.

The task to convert biomass into long-term carbon deposits seems challenging but is in our opinion in fact manageable. About 14 billion tonnes of biomass per year are produced in agricultural cycles, of which 12 billion tonnes per year are essentially thrown away as by-products. Examples of such product-by-product pairs are grains and straw, orange juice and peel, or oil seed and the rest of the plant. Even in an industrial country like Germany, the treatment of highly defined waste biomass such as from sugar-beads (4.3 million tonnes sugar per year), rapeseed production (3.5 million tonnes oil per year), or clarification sludge (3.0 million tonnes per year) could potentially lower German CO_2 emissions by about 10 %. Most impressive are the big contributors: for every 100 million tonnes of Brazilian sugar produced per year, about 1 billion tonnes of bagasse (fibre left over after sugar extraction) are thrown away and burned. Considering that only one product of one country could significantly contribute to reductions in CO_2 emissions, the use of such waste products seems promising. It is important to stress that not the main but the by-products of agro-industry and foodcrop cultivation are used. This means that there is no competition between food and energy production, yet rather a synergy between the two consumption pathways.

Besides laying the ‘raw material base’, the ‘technology base’ also has to be created. Work on ‘carbonization’ is still a rare, but luckily growing, research topic. Geological coalification, i.e., the transformation of plant material to coal, is not the ‘hot charring’, as practiced by a charcoal burner, but rather a more effective ‘cold’ coalification, which occurs on the timescale of some hundred (peat) to hundred million years (black coal). Due to its slowness, it is usually not considered in renewable energy exploitation schemes or as an active sink in the global carbon cycle.

Different technical solutions have been tested to imitate coal formation from carbohydrates employing faster chemical processes. Classical ‘hot charring’, as practiced by a charcoal burner, is technologically restricted to a high-value starting product such as dry lignocellulosic materials (essentially wood). All other plant waste, especially leaves, fine fragments, and all wet plant and bacterial waste are not directly suitable for classical charring. Nowadays, a great variety of pyrolysis[1] technologies, including hydrous pyrolysis[2], are available which can transform biomass feedstock into biochar[3], gases, and/or liquids. There are also more modern biomass technologies such as biomass-to-liquid (BtL) to transform biomass into biofuels. These, however, require high input in equipment, process management or feedstock treatment, and they may even release significant amounts of greenhouse gases.

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[1] Pyrolysis refers to the chemical decomposition of material through extreme heat.

[2] Hydrous pyrolysis refers to pyrolysis in the presence of water. Water reduces the required energy to break down components during pyrolysis.

[3] Biochar is a charcoal produced from any kind of biomass. For examples of biochar production technologies see http://www.pronatura.org/projects/green_charcoal.pdf, http://www.eprida.com, http://www.enertech.com/technology.

Hydrothermal carbonization

Application of 'geological' conditions, i.e., weakly acidic pH values and exclusion of oxygen in closed deposits at high pressures and moderately high temperatures in water, leads to so-called hydrothermal carbonization (HTC) (see Fig. 1). HTC is an especially promising process as regards conditions, costs, efficiency and even ecology. Modern versions release practically no greenhouse gases and allow close to 100 % binding of the carbon from the biomass in the final product. First experiments were carried out by Bergius, who described the hydrothermal transformation of cellulose into coal-like materials as early as 1913 (Bergius *et al.,* 1913). More systematic investigations were performed by Berl and Schmidt, who alternated the source of biomass and treated the different samples in the presence of water at temperatures between 150 °C and 350 °C. Their series of papers published in 1932 summarized contemporary knowledge about the emergence of biocoal synthesis (Berl *et al.,* 1932 a; Berl *et al.,* 1932 b). Later, Schuhmacher, Huntjens and van Krevelen (1960) analysed the influence of acidity on the outcome of the HTC reaction and found large differences in the decomposition schemes, as identified by the carbon to hydrogen to oxygen ratios of the final product.

$$\text{HTC:}\quad \underset{\text{carbohydrate}}{C_6H_{12}O_6} \rightarrow \underset{\text{'biocoal'}}{C_6H_4O_2} + \underset{\text{water}}{4\,H_2O}$$

$$\text{Charring:}\quad \underset{\text{carbohydrate}}{3\,C_6H_{12}O_6} \underset{\text{oxygen}}{+\,16\,O_2} \rightarrow \underset{\text{'biochar'}}{C_6H_2O} + \underset{\text{combustion gases}}{14\,CO_2 + 4\,CO} + \underset{\text{water}}{17\,H_2O}$$

Fig. 1. Chemical principle of hydrothermal carbonization (HTC) as opposed to classical charring. HTC: under temperature and catalysis, carbohydrates (here glucose) are converted into biocoal and water only. Charring: carbohydrates are partly burned in presence of oxygen ('pyrolysis'), leaving a char residue and combustion gases. The sum formula of biocoal and biochar are simplifications and depend largely on the reaction conditions. The carbon efficiency (i.e., the proportion of carbon that is converted into the end product) of HTC is close to 1, while in biochar formation carbon efficiency is only about 0.20 – 0.35 due to the presence of oxygen.

A renaissance of such experiments started recently with reports on the low temperature ($\leq 200\,°C$) hydrothermal synthesis[4] of carbon spheres using sugar or glucose as a starting product (Wang *et al.,* 2001; Sun *et al.,* 2004). Recently, it was found that the presence of metal ions can accelerate this type of reaction. This catalysation shortens the reaction time to some hours and directs the synthesis towards

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[4] Hydrothermal synthesis refers to the synthesis of material from liquid solutions.

various morphologies and carbon structures (Qian *et al.,* 2006; Yu *et al.,* 2004; Cui *et al.,* 2006). It was also investigated whether the presence of ternary components in complex biomass (such as orange peel or oak leaves) alters the properties of the synthesized carbon structures (Titirici *et al.,* 2007; Titirici *et al.,* 2007 b). Unexpectedly, it was found that the presence of these components improved the properties of the end products for certain applications: benefits such as a smaller structural size of carbon dispersions and porous networks, higher hydrophilicity of the surfaces and higher capillarity emerged. These properties are especially important if biocoal is used in soil applications to increase water and nutrient storage capacity.

This acceleration of HTC for coalification makes the process a considerable, technically attractive alternative to other currently discussed carbon sequestration techniques (such as biomass burning combined with carbon capture and storage), applicable at the required scale of billion tonnes of carbon sequestered per year.

To summarize the outcome of the scientific optimization trials, catalysed HTC just requires heating of a biomass dispersion under weakly acidic conditions in a closed reaction vessel for two to twenty-four hours at a temperature of around 200 °C. This is indeed an extremely simple, cheap and easily scalable process.

HTC also has a number of other practical advantages. Once activated, HTC is a spontaneous, exothermic process. It liberates 10 to 30 % of the chemical energy stored in the carbohydrates throughout dehydration (depending on conditions; this is due to the high thermodynamic stability of water). The exothermic character was already described in the first work on HTC by Bergius who warned of the violent character of the reaction! HTC also inherently requires wet starting products or wet biomass as effective dehydration only occurs in the presence of water. Since coal binds water only marginally, the final carbon can easily be filtered off the reaction solution. This way, drying schemes or more demanding isolation procedures can conceptually be avoided (even when using very wet starting products such as freshly harvested algae). Under acidic conditions and below 200 °C, most of the original carbon is recovered as solid biocoal. Carbon structures produced with HTC, either for deposit or material use, are therefore highly CO_2-efficient. Large-scale technical solutions for HTC have been developed but are not yet available on the market.

The vision of decentralized CO_2-sequestration plants and potential CO_2-negative products

The simple, cheap, and scalable process of HTC in principle allows the layout of machines operating in a communal or decentralized context, and even mobile, container-type machines can be considered. For rough numbers supporting this vision, it is to be remembered that HTC is inherently exothermic and therefore an energetically ‘free’ process, but requires that the biomass is heated to 200 °C at the beginning. The latter can in principle be combined with the cooling of the coal and water mixture at the end. Since this type of heat management can only be efficiently implemented for a machine of a certain size, energy management plus machine investment costs define the optimal level of decentralization. In our opinion, a ‘low-tech’ realization will have the size of a relatively large container, which could convert 2000 – 10 000 tonnes of biomass per year to coal. Around 2000 tonnes of biomass are typically produced on a land area of 200 hectares (or 2 km^2), which means that bioenergy generation and carbon sequestration including transport pathways could easily be a decentral or rural measure. HTC can therefore be considered as a communal, agricultural or forestry task rather than a typical industrial operation, with many machines working in parallel. To compensate the amount of CO_2 produced globally by burning fossil fuels each year, about two million HTC machines would be needed (much less than the number of waste water treatment plants in the world or the number of new cars sold in Germany every year).

But what can be done with all this biocoal? Biocoal generated by HTC is a product with a spectrum of possible uses. Biocoal is, for instance, a high quality energy carrier, which is easy to store and rather safe to handle and transport at the same time. Its calorific value is typically between 24 and 32 MJ/kg, which is much higher than that of low quality coal. In contrast to fresh biomass, storage is not complicated by the risk of mould, ignition or decomposition. It is also an advantage that biocoal is artificially produced: the HTC process can be directed to produce coal fuels with special properties, for instance, a very low ash content, a sulphur-free character, or a very fine particulate morphology. Thus, it can be burned for local energy or heat demand or used for industrial operations such as steel manufacturing, where high quality coal is needed and marketed. Such operations are clearly meaningful for less developed countries as they can replace expensive energy imports and can create a distinct base of wealth through trading biocoal at local levels. For the chemical industry, HTC coal (as all coal) can be transformed via gasification and the Fischer-Tropsch process into oil intermediates, thus keeping the chemical industry running like it does today. The Fischer-Tropsch process, however, is rather inefficient: only about 50 % of the primary chemical energy ends up in liquid fuel. Nevertheless, this can be economically meaningful, assuming an oil price close to USD 100 per barrel. However, this application of biocoal ‘only’ satisfies the need of the chemical industry for raw materials and the demand of the transportation sector for liquid fuels. All these operations are CO_2-neutral and can replace fossil resources, but they are definitely not CO_2-negative.

For the desired CO_2-negative products, biocoal has to be applied in long-lasting, large-scale material applications. Employing it as a construction additive to improve concrete building materials or pavements (where currently waste products of the oil industry are used) is certainly one option. Even more promising is its use as 'sorption coal' for the purification of drinking water and the improvement of soil.

'Carbonaceous soil' is presumably the largest active carbon sink of the Earth system. The highest carbon concentrations in the soils are generally found in the northern, colder latitudes rather than the tropics.[5] The only exceptions are the Amazonian dark earths, called 'terra preta', which have up to 70 times higher soil carbon contents than the surrounding soils (Glaser, 2007). Interestingly, the organic matter of these soils does not originate from natural biomass litter but from large amounts of charred materials, the residues from biomass burned many hundreds of years ago by pre-Columbian Indians (Sombroek *et al.,* 2004). The 'terra preta' soils are highly fertile: they exhibit high nutrient storage, retention capacity and base saturation (Titirici *et al.,* 2007 a; Titirici *et al.,* 2007 b) due to the physical sorption and textural properties of the charcoal. These carbon fractions have remained in the soil because they are not easily decomposed (Lehmann *et al.,* 2003; Glaser *et al.,* 2002).

Soil researchers have already proposed the 'terra preta' concept, which involves using artificial biocoal to enrich soil, creating a potential carbon sink of global dimensions and improving soil quality and plant growth at the same time. Biocoal production is more effective at sequestering carbon than the natural carbon fixation by afforestation, which is accepted as a carbon offset measure under the Kyoto Protocol (see Liverman, this volume). In contrast to fixing carbon in soil biomass, fixing it in the form of coal is a lasting solution: lignite or black coal (contrary to peat) is hardly biodegradable. The question of potential destabilization of coalified carbon is currently being assessed in more detail (Cheng *et al.,* 2006).

The combination of biocoal production for energy and 'terra preta' use may therefore be seen as a perspective for mitigation of climate change and restoration of abandoned land. Instead of clearing the rainforest for questionable palm-oil production (Pearce, 2005, p. 19), a 'carbon-reinforced rainforest' would produce even more energy, stored in wood or coal, while being CO_2-negative and supporting biodiversity at the same time. A non-linear benefit results from a 'biological amplification' of the original chemical efforts. It is estimated that 10 tonnes of biocoal per hectare are sufficient to remarkably improve depleted soil. Consequently, larger amounts of carbon can be bound in the growing biomass, which can then be used as a CO_2-neutral energy source. The scientific development of methods to adjust biocoal properties might accelerate and improve this process and thereby secure the productivity of farmland even under altered climatic conditions. The demand for such carbonaceous soil additives easily sums up to billions of tonnes per year and also represents a high economic value.

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[5] http://biocharfund.com/index.php

Economic and socio-economic impacts

Is this solution economically feasible? The question is especially pertinent in the case of applying HTC biocoal as a soil additive, given that the generated carbon is essentially just ‘thrown away’. We have calculated that spending just 10 % of our current expenses on oil might be sufficient to compensate the global annual emissions of fossil CO_2 by biocoal production. This calculation assumes carbon fixation costs of USD 75 per tonne, a target that in our opinion can be met. (HTC is essentially just heating an aqueous dispersion, a process that generates part of the energy itself). These cost estimates do not take into account the added value for the geosystem or agriculture. Lehmann (2007) concluded that biochar sequestration by classical charring technology in conjunction with bioenergy generation from pyrolysis becomes economically attractive when the value of avoided CO_2 emissions reaches USD 37 per tonne (equal to about USD 130 per tonne biochar). This is cheaper than the presumed costs for carbon capture and storage technology (Enkvist *et al.,* 2007). The economic attractiveness might be further improved if biocoal is sold as a soil conditioner, as it is already done with peat for ornamental gardens in home improvement stores.

The cost of using biocoal as a soil additive would have to compete with the cost of using it as fuel or as raw material for the Fischer-Tropsch process. Within subsidy schemes like the German Renewable Energies Act biocoal is classified as a renewable fuel. Therefore, biocoal from waste would probably first be used in heavily subsidized power stations. Balancing or lowering subsidies to allow for the use of biocoal in soil applications is a potential political countermeasure that would also save taxpayers’ money.

As discussed above, biocoal generation can be considered a communal, agricultural or forest operation. The end-products of HTC, i. e., biocoal and fertilizer (gained as a side product from the mineral part of the plants), have to be marketed where they compete with other fuels or other fertilizers. If the market is regulated properly, the small-scale technology of biocoal production seems to be extraordinarily eligible for developing countries. The combination of high amounts of low value biomasses, large areas of poor and abandoned soils, high growth potential, and high relevance of bioenergy in the tropics particularly fit the biocoal approach. Current non-sustainable markets could therefore easily be transformed into sustainable ones, especially in tropical regions. The classical biochar concept has already been adopted by organizations like Pro Natura International[6] or the Biochar Fund, which is dedicated to fighting hunger, energy poverty, deforestation and climate change.[7]

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[6] http://www.pronatura.org/index.php?lang=en&page=index

[7] http://biocharfund.com/index.php

HTC in combination with modern biomass production schemes (such as agroforestry and agro-industrial cultivation of algae) may lead to significantly higher productivity on agricultural soils, restoration of abandoned areas, and an expansion of bioenergy options. ‘Slash and char’ instead of ‘slash and burn’ (Steiner, 2007) not only reduces anthropogenic CO_2 emissions by providing biochar as a long-term carbon sink, it also improves soil fertility and yield potential. Biocoal from HTC potentially allows farmers in many eco-regions (not only in the humid tropics) to escape from the cycle of declining productivity and soil degradation, which result from shortened fallow periods. Continuous cultivation or cultivation with only very short fallow periods may be possible (Steiner, 2007). Permanent cropping with higher yields and income instead of shifting cultivation might significantly change economics and politics of agriculture.

In this way, HTC may represent a technology leap out of the ‘problem triangle’ composed of accelerating climate change and the growing demand for energy and raw materials. Optimally, this new technology would allow for a transition without violating social and human-rights issues, exerting a major economic impact and strongly benefitting poor countries rich in biomass and other rural areas of this planet.

Summary

This essay presented the concept of a ‘CO_2-negative industry’ based on agricultural and forest waste, which, in principle, has the potential to counterbalance CO_2 emissions produced by using fossil fuels. In this way, passive utilization of the atmosphere as a sink could be replaced by ‘atmospheric management’ that can deliberately control the CO_2 level. Bioenergy and bio-raw-material production might also resolve a number of energy and resource problems, even though it will not be enough to meet all of our energy needs. For a complete solution to our energy problem we will still need to transform our fossil-fuel-based industry into a renewable energy system. In the vision presented here, waste biomass is converted in a highly decentralized fashion on the community scale, potentially by hydrothermal processes, into valuable carbon products that are safe and have long natural lifetimes. We considered the case of biocoal as a soil additive, a use which holds promise for applications worldwide and potentially to brings about ‘biological amplification’ through increased soil fertility. There are also a large number of other options for the use of biocoal that are worth analysing, such as the purification of drinking water by sorption coals or the improvement of building materials by carbon additives. These options could reach a scale and importance similar to that of soil applications.

However, the most important message is that such technology truly has the potential to be implemented, as it does not hurt or violate current political or economic interests. The creation of an *additional* industrial scheme that compensates the imbalance caused by currently applied processes while creating *additional* value and products is usually accepted. The reason is that it is in line with the impetus of society, and it does not ask for cutbacks or modification of behaviour. Clearly, it does not change the 'name of the game' but sustains further economic growth.

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