

01-00: Biomass for energy – Over-all aspects

Since the report “Our common future” was presented by the “Brundtland commission” in 1987 has sustainability been on the agenda in many counties of the world. A sustainable development must – according to the definition given in the report – guarantee that each and every generation is given the possibility to fulfil their (essential) needs without compromising the possibility for any following generation to fulfil their needs. The sustainable development must be based on three pillars, namely 1) Ecological sustainability, 2) Social sustainability and 3) Economical sustainability.

The global warming and it’s consequences as foreseen by the climate models reported by the IPCC violates the ecological sustainability by replacing known ecosystems by unknown and by shifting climate zones in a way that may render areas that are today densely populated uninhabitable for humans.

It violates the social sustainability for the same cause, threatening to expose large populations to extended starvation or force them to abandon their traditional land.

It violates the economical sustainability by threatening to increase costs for climate-induced catastrophes and migration.

According to a vast majority of climate researchers is carbon dioxide one major agent in the ongoing climate change process. All statistics, regardless of source, do also agree than the major source of carbon dioxide from human activity is our collective use of fossil fuels; coal, oil and gas.

01-00-01: Greenhouse effect – a delicate balance

Anything that has a temperature above absolute zero (-273.15 °C) will emit thermal radiation. This is the phenomenon behind that you can today buy optical thermometers that can be used to sense the outside temperature of a building, for instance, at a distance. Such thermometers collect the infrared (i.e. the heat) radiation by a lens, focus the radiation on a sensor and use that sensor signal to calculate the temperature.

At low temperatures is this radiation very long-wave and low-intensity. The hotter the object becomes, the shorter becomes the wavelength and the higher the intensity and at temperatures around 5-600 °C is the intensity so high that we can start seeing the long-wave radiation as a dark red glow. Further heating shortens the wavelength and the colour shifts to orange, to yellow, brighter and brighter yellow, bright yellow with a touch of blue and – finally – approaches white. At the same time increases the intensity.

The sun is very hot, approximately 6000 °C, and emits white light at a very high intensity. As this light hits the earth, it is absorbed partly in the atmosphere, partly in vegetation and in soil and partly in water. Part of the incident solar radiation is also reflected back into space and not absorbed at all. As light energy is absorbed it is transformed to heat and the earth becomes warm. It is a fairly straightforward calculation to set up an energy balance for the earth if it is assumed that there is no atmosphere at all but all the incident solar radiation (*irradiation*) is assumed to be absorbed. Doing such a simple calculation results in a mean temperature on earth which is about -10 – -15 °C.

In reality is the mean temperature of the earth a few degrees plus, on the Celsius scale. The difference is due to the natural greenhouse effect.

The gas mainly responsible for the natural greenhouse effect is water vapour. Water vapour has the property to be almost transparent for short-wave radiation while it absorbs longer wavelengths. Hence is the short-wave solar radiation coming from the sun allowed a free passage down to ground level while the long wavelength radiation from the soil and from the surface of the seas, radiation that should really leave the earth again, is absorbed in the atmosphere. That means that the atmosphere becomes warmer. The glass panes in a greenhouse have exactly the same property: They allow solar heat to enter the greenhouse but they hinder it from passing out again. Carbon dioxide together with a number of other gases (methane and sulphur hexa-fluoride just to mention two) has similar properties as water vapour and will therefore enhance the natural greenhouse effect. This is the problem.

Increasing the concentrations of so-called greenhouse gases in the atmosphere will lead to an increase in the greenhouse effect. There are mechanisms that work in the opposite direction: For example will small particles, such as small soot particles, help to reflect part of the irradiation back to space, and then will the absorption be decreased. Similarly will an increased cloudiness counteract global warming.

So far, measurements indicate that the global mean temperature is increasing and the best agreement between measured temperatures and temperatures calculated from theoretical climate models require that the models are fed with data covering not only natural variations, like volcanic eruptions and such, but also with the emissions from mankind ever since the start of the industrial revolution. If any of these two datasets is omitted, the climate models can not reproduce the measured temperatures. Hence the IPCC concludes that man-made emissions do play an important in the current temperature trend.

The time-scales in the world's climate system are very different. While global temperatures in the atmosphere may change "rapidly", i.e. within years, may it take centuries for the whole water volume in the seas to change it's temperature. The greenhouse gases do also have a different behaviour over time. Concentrations of water vapour change very rapidly by evaporation from the seas on hot days and by rain. Carbon dioxide, though, stays in the atmosphere for decades and centuries, like many of the greenhouse gases mentioned in the Kyoto –protocol. Therefore, it can take only short time – decades – to induce such effects on the global climate that will remain for centuries.

01-00-02: Carbon circulation – another delicate balance

Carbon is an element of fundamental importance to any form of organic life. Carbon, oxygen and hydrogen are the main elements in the hydrocarbons making up any living tissue; plants or animals alike. As organisms grow bigger, carbon is bound in living tissue, as they die and finally deteriorate, that same amount of carbon is again released from the dead tissue.

01-00-02a: The photosynthesis

The most important mechanism to bind carbon in living tissue is the photosynthesis. Through photosynthesis is carbon dioxide absorbed from the atmosphere into growing plants. Together with water and with solar energy does the carbon dioxide form energy-rich sugars that the plants need and which are in turn transformed into other substances like the cellulose we use for clothes (*cotton and flax are nothing but cellulose fibres*) and for paper, they are formed into wood (*wood consists of celluloses and another substance called lignin*) that we use for building and constructions, and for other purposes. As a by-product from the photosynthesis is oxygen produced and released into the atmosphere.

The word photosynthesis has not a unique meaning, but there are three different kinds:

- In temperate and sub-polar areas, the vast majority of naturally occurring plants use the so-called C₃-photosynthesis for carbon fixation. Among these are the typical trees in the temperate and boreal climate zones, birch (*betula*), ash (*fraxinus*), beech (*fagus*), pine (*pinus*) or spruce (*picea*) just to mention a few. The process is called C₃ because major intermediates are molecules containing three carbon atoms.
- To cope with hot and/or arid climates, another type of photosynthesis has developed, namely the C₄-photosynthesis where the first intermediates are instead molecules with four carbon atoms. The C₄-process uses an additional enzyme which is highly efficient to capture carbon dioxide from the atmosphere also when the concentration in or near the cell is low. In dry and hot climates, the plants will minimize perspiration by closing their stomata and in that case, the CO₂-concentration inside the cells in the foliage becomes low. Thus, plants subject to such conditions – like sugar cane (*saccharum officinarum*), maize (*zea mays*) and several other commercially very important species – have developed the C₄-photosynthesis for their survival.
- Succulent and water-storing plants that are adapted to extremely arid conditions – cacti (*cactaceae*), for example – have developed another, even more sophisticated, process to make efficient use of carbon dioxide without losing too much water through cell respiration – but these plants are of no interest from an energy point of view. These are called CAM-plants.

Regardless of the details in the photosynthesis process, the net effect is that carbon dioxide and water combine to store solar energy in the form of sugar which is then successively further transformed into cellulose, hemicellulose or other compounds. To transform carbon dioxide and water into glucose and cellulose, the plant needs use a number of enzymes, proteins and organic amino acids, chlorophyll being one of the most well-known actors.

01-00-02b: The natural carbon loop

Organisms that cannot directly bind carbon from the air to form new living tissue during their growth are depending on reserves of previously bound carbon for their growth. Cows and pigs are two examples of such organisms:

Cows – like many animals – are *herbivores*, they rely completely on a vegetable diet for their supply of carbon and energy to support their growth and their life. A major part of the food they eat is cellulose and their digestive system is constructed to be able to digest cellulose and break it down into the smaller fragments they need to build up the proteins, fats and other substances that they need to sustain life.

Pigs – again like many animals – are *omnivores*. Their digestive system can to some extent digest cellulose but is designed to work at its best with a mixture of proteins and fats easiest found in a mixed diet composed of plants and animal proteins.

Regardless, the carbon found in any growing or living organism was almost exclusively originally removed from the atmosphere and bound in a growing plant by aid of the photosynthesis. That same carbon may then have passed several organisms before it ended up in – say – a lion or a hyena or it may have been bound by the photosynthesis and then have found a direct use already in the first form, such as the carbon in olive oil or in a cotton fibre.

As an organism dies and the organic material again deteriorates, it is slowly transformed back again into the original constituents that were used up and absorbed during the photosynthesis: water and carbon dioxide. The process may be very slow as in a desert where organic materials like fragments of clothes and pre-historic textiles have been found after thousands or years or it may be fast as in household composting. Just as oxygen is released during the formation of new organic material in the photosynthesis is oxygen consumed during the deterioration, and the amounts are equal. Just as much energy is bound during the formation of new organic material in the photosynthesis as is released during the deterioration.

The slow and natural deterioration of organic material may now be replaced by a fast and controlled process that we call *combustion*. This will be dealt with in more detail in column 4 of this handbook. The advantage with combusting the organic material instead of just leaving it to deteriorate slowly is that we can make practical use of the energy released during the process – while that is very difficult to do from the slow and biological deterioration. Dry biomasses – or in general – herbaceous and woody biomasses, are easiest dealt with using direct combustion to extract the energy – the second and third rows in the handbook.

Combustion is basically a one-step process: A fuel is brought into intensive contact with the correct amount of oxygen, the mixture is ignited and then the process is allowed to run to completion.

Other thermochemical processes – such as gasification, pyrolysis or torrefaction – differ from combustion in the respect that the combustion process is split into steps: First is the fuel partially combusted. This is the same as to separate it into gaseous, liquid and solid components, all at a high temperature. Then are these components combusted separate in one or more later steps. The second step may either occur in close connection to the first step and at the elevated, primary process temperature, or the gaseous liquid and solid components may be allowed to cool down to a lower temperature prior to the final combustion, either at the same site or at another site.

Generally speaking, this kind of separated combustion will yield a lower total efficiency since each process step tends to introduce losses. The advantage sometimes strived for is that the final combustion process of the most high-grade fuel fraction may yield higher temperatures and a cleaner fuel than would have been the case if the process was not staged. Finally, however, the total energy released from the biomass can not exceed that bound by the photosynthesis and, obviously, the total amount of carbon remains the same... Again, this is dealt with in column 4 of the handbook.

If the biomass is left to deteriorate in open air it will do so in a surrounding where oxygen is abundant and it will finally be decomposed completely into carbon dioxide, water vapour and energy. If, however, the access to oxygen is limited so that there is an oxygen deficit, the biological processes will lead to an energy-rich product gas. This is called anaerobic digestion and is, for some types of biomass, the most efficient process to extract the energy in a useful form. The main energy-carrying constituent of the gas will be methane which is also the main constituent of so-called natural gas. Hence can a purified product gas from anaerobic digestion be treated just as “natural gas”, it can be liquefied and distributed as bottle-gas, it can be used as a car fuel or it can find other applications. The biomasses best suited for this treatment are dealt with in row 3 in the handbook – putrescible biomasses. Again, the total energy released and the total amounts of carbon are both limited by what was absorbed during the photosynthesis. No extra carbon and no extra energy is added to the material by the biochemical treatment.

For mixed biomasses either process may be the best: Direct combustion in some cases, split thermochemical process in some cases and biochemical treatment in some cases. This will be strongly dependant on the actual composition of the material and is dealt with in row 4 of the handbook.

So the use of biomass for energy purposes is – put in the simplest way – to substitute the slow deterioration occurring spontaneously in spread-out, dead, material, by a fast and forced process occurring in an enclosure where we can make practical use of the energy released.

The total process may occur in several steps but that makes no real difference:

- The amount of released energy is not altered but is still exactly the same as that once bound through photosynthesis.
- The amount of released carbon is not altered but is still exactly the same as that once bound through photosynthesis.
- The amount of released hydrogen is not altered but is still exactly the same as that once bound through photosynthesis.
- The amount of consumed oxygen is not altered but is still exactly the same as that once released through photosynthesis.

The only thing that changes is that the process takes place within seconds, minutes or hours instead of decades and that – hence – the temperatures obtained amount to several hundreds of degrees Celsius instead of only a few degrees as obtained in a household compost. This makes the energy useful for us – but it does not affect the natural carbon loop.

The global measure to maintain the natural carbon loop, as long as no more carbon is added to it, is to maintain the global potential of carbon capture in forest growth and in growth of other organic materials. As long as the carbon capture capacity is maintained and no extra carbon is added to the loop, then carbon binding in growing biomass will, in the long run, balance the carbon release.

There is also a slow but natural carbon loop, partly outside the organic materials. This loop concerns mineralized carbon and the carbon found in shells, such as mussels' shells, or bones. Such animal parts, containing bound carbon in the form of carbonates, will slowly mineralize to form limestone and the limestone is in turn mined and used in a number of industrial processes.

The cement industry is one good example. The production of cement involves calcining limestone at elevated temperatures (6-900 °C) and then sintering it together with some additives at high (1400-1450 °C) temperatures. Today, mainly fossil fuels are used to achieve the temperatures needed and approximately 50 % of the carbon dioxide released (typically 0.7 – 1 kg CO₂/kg cement) originates from the fossil fuels used while the remaining 50 % originate from the limestone and from the calcining process.

Hence; To abate excessive release of carbon dioxide and restore the natural carbon loop balance, we need not only consider the choice of fuels in different processes but we also need re-consider the raw materials used, to increase the re-use and re-circulation of materials once produce and maybe develop new processes.

01-00-02c: The carbon loop with fossil fuels

As opposed to what was said in 01-00-02a, the fuels we today call “fossil” were basically formed some 100 million years ago. This means that the carbon bound in these fuels was bound by the photosynthesis ages ago but is released into today's carbon loop. The phrasing “today's carbon loop” refers to the carbon circulating, balanced over the last one hundred years. One hundred years is (about) the generation time for trees growing in the sub-arctic region and hence we use that as a global and common basis for the carbon loop. So carbon bound and released within one siècle is considered to be in balance while carbon older than that is considered as being an addendum to the cycle. Of course this limit is not strict but an average. One hundred years is an arbitrary number chosen to represent a slow-growing but, from a global point of view, large ecosystem, namely the boreal taiga.

You will now realize that fossil fuels – from a carbon balance standpoint – represent mineralized carbon and may hence, from the carbon balance standpoint, be seen as similar to limestone. It simply forms part of the very slow, but natural, loop containing mineralized carbon.

It can then be argued that other uses of mineralized carbon – such as the use of limestone for cement clinker manufacturing – should be just as much in focus as the use of fossil fuels. The reason that this has not yet happened is basically that it is, so far, considered much easier to replace fossil fuel use by new methods for the production of energy carriers and energy services than to replace the use of e.g. limestone as the basis for cement manufacture.

Regardless of source and process, the release of mineralized carbon into the atmosphere will increase the amount of carbon circulating in both the short carbon loop, i.e. the one involving growing biological matter, and will also, slowly, increase the rate at which carbon becomes bound in mineral form. The short and fast carbon loop, involving living and dead biomass, the oceans and the atmosphere, is the one that affects the climate.

To maintain the short-term balance (i.e. the balance as seen over one century or about) there would be a need to increase the carbon binding capacity so as to store the carbon in bound form and not allowing the excess carbon to raise the carbon dioxide concentration in the atmosphere. The oceans play an important role in this since the vast amounts of water in the oceans has the capacity to dissolve enormous amounts of carbon dioxide, and this is also happening. Unfortunately, this also has negative effects and coral reefs are reported to show damages that may partly be attributed to an increase of the carbon dioxide concentration in sea water.

The other main way to increase the global carbon binding capacity would be to allow the land-based biomass reserve to increase. The major land-based and carbon-binding ecosystem world wide is forests – tropical forests, temperate forests and boreal forests. If the total amount of standing trees, as measured in tons or m³ of solid, living, timber, was allowed to increase, then that would represent a storing of carbon. Unfortunately, this is not the case in reality but deforestation is still occurring on a global scale.

01-00-03: Bioenergy and the environment

At a global scale, the photosynthesis produces about 150 000 000 000 tons of dry cellulose every year, 150 billion tons. The harvesting and the use of this biomass for energy purposes does not in itself represent any contribution to the carbon circulation, but in case the harvesters or the transport system to supply the biomass to the end users makes use of fossil fuels – such as diesel oil for the trucks to transport the biofuel or to run the harvesters – then there will still be a net contribution to global warming also from biofuels.

Hence the use of biofuel is not completely carbon neutral but will be depending on the infrastructure.

The environmental concerns with biomass use tend to fall into four major questions:

- Does the extraction of biomass for energy threaten the commercial use of biomass for other purposes?
- Does an extended use of biomass for energy threaten the supply of food for the ever-growing population of this world?
- Does an extended use of biomass for energy threaten the biological diversity?
- Does an extended use of biomass for fuel increase the emissions of other unwanted gases and pollutants, such as nitrogen oxides, soot and alike?

It is obvious that the answers to these questions are to a great extent depending on local, regional, national and international policies and system strategies.

The first priority as it comes to choice of biomass fractions suitable for local/regional biomass-based energy solutions should of course be to use such fractions that can be co-produced with food and with commercial crops. From that, it follows that large-scale monocultures should be avoided. The system solution – logistics as well as the choice of raw-material – shall simply be chosen so as to avoid competition and to promote co-production.

As the fourth question is concerned, it must be understood that the choice of process, direct combustion, gasification, high-temperature pyrolysis, low-temperature pyrolysis (torrefaction) or any other process, and the choice of process equipment must be apt to the biomass in question.

Provided that the equipment is well-suited for the biomass in question and provided that the process control system is correctly tuned, the environmental impact from the thermal processing can be kept under close control and need not cause any worry.

However, inadequate equipment or process control, in combination with the varying quality with biomass fuels, may prove disastrous to the local environment and to the air quality. The text sections in column 4, chapter 04-00, will bring these aspects up to discussion in some detail.

01-00-04: Bioenergy and economy

Biomass is – as made clear in the text section about the photosynthesis – produced over vast areas and is available in low concentrations. The upper limit for photosynthesis (C_3) production is some 50-100 tons of dry substance per hectare and year. This limit is never reached in practical cases, but growth rates are typically rather less than 30 tons of dry substance per hectare and year and they are strongly latitude dependant so that the rates at sub-polar latitudes may be as low as 1-3 tons.

Also in regions where agriculture for food and/or fibre is intensive may the actual, areal, production rate be low. Just assume, for example, that the fuel is co-produced with sugar. The sugar beet may well have a growth rate at – say 10 tons dry substance per hectare and year but the residues available for energy amount only to (approximately) 30 % of this amount and hence to 3 tons/ha-year. Hence this is the rate of *fuel* production and you will notice that this is significantly lower than the *biomass* production. Different types of utility crops will exhibit different residue-to-yield ratios. You will find these things dealt with in more detail in chapters 02-02 and 03-02.

Generally speaking, however, logistics are a cost-determining factor in bioenergy systems, its influence to the total cost being much more determining than it is in fossil-fuel based systems. To counteract the logistic cost, bioenergy systems must always be designed so that the total efficiency is maximised. They must also be sized in accordance with the limits set by logistic costs, and hence they cannot be too large.

The total cost structure with biomass-based energy systems hence become very different from that experienced with fossil-fuel based systems and the fifth column in the handbook will provide you with some first insights to how this can look. You will observe that column 5 will contain no detailed cost estimates but will be devoted to indicate over-all cost structures.