Biomass-based Control of the CO_2 Concentration in the Atmosphere

Josef Spitzer, Graz University of Technology, Institute of Innovation and Industrial Management Kopernikusgasse 24, Graz, josef.spitzer@live.at; **Lorenza Canella,** Joanneum Research Graz, LIFE Institute for Climate, Energy and Society Management Waagner-Biro-Straße 100, Graz, lorenza.canella@joanneum.at

Abstract: Biomass offers two options for controlling the CO_2 concentration in the atmosphere: Storage of solar energy to substitute for fossil energy („bioenergy technologies, BET") and absorption of atmospheric CO_2 combined with a permanent storage ("negative emissions technologies, NET"). The BET option has been investigated in detail by research and industry over the past 40 years. A number of applications have reached commercial status. The success of this option depends on three properties of the biomass feedstock: time constants of growth and decay processes (time delay), energy yield per unit of carbon (carbon intensity) and secondary effects (upstream processes, land use change). These properties depend on the kind of biomass used as feedstock, i.e. purpose-grown biomass or by-product biomass. The goal of NET options is a reduction of the atmospheric CO_2 concentration typically in a one-off effort, after a zero CO_2 emissions status has been reached at a concentration level above the limit set for stabilizing the global temperature increase at 1.5 to 2°C. They have to fulfil three conditions: existing carbon fluxes and stores in the biosphere are not affected by the operation of NET (additionality); carbon sequestered by NET has to be registered and allocated to NET operators (carbon credits registration); NET carbon registered in the credits system has to be prevented from re-entering the atmosphere (permanent storage). Model calculations have been performed allowing the quantification of the effect achieved with BET and NET options. The results show that wood based BET options replacing fossil fuels take up to several decades before the full benefit of emission reduction is achieved. Establishing NET options may take a number of years; as an example, increasing the existing production forest stock (164 GtC) by 10% and permanently storing the increase may decrease the CO_2 concentration in the atmosphere by approx. 8 ppm. Besides techno-economic questions, the success of biomass-based control of the CO_2 concentration in the atmosphere strongly depends on the time required for the options to be in place and to effectively contribute to reaching the emissions reduction goals, e.g. "2030" and "2050".

Keywords: biomass-based control, carbon dioxide concentration, bioenergy, negative emissions, carbon credits

1 Introduction

Biomass offers two options for controlling the CO2 concentration in the atmosphere: Storage of solar energy to substitute for fossil energy („bioenergy technologies, BET") and absorption of atmospheric CO_2 combined with a permanent storage ("negative emissions technologies, NET").

The BET option has been investigated in detail by research and industry over the past 40 years. A number of applications have reached commercial status. The success of this option depends on three inherent properties of the biomass feedstock: time constants of growth and decay processes (time delay), energy yield per unit of carbon (carbon intensity) and secondary effects (upstream processes, land use change). These properties depend on the kind of biomass used as feedstock, i.e. purpose-grown biomass or by-product biomass.

The goal of NET options is a reduction of the atmospheric CO_2 concentration typically in a one-off effort, after a zero CO_2 emissions status has been reached at a concentration level above the limit set for stabilizing the global temperature increase at 1.5 to 2°C. They have to fulfil three conditions: existing carbon fluxes and stores in the biosphere are not affected by the operation of NET (additionality); carbon sequestered by NET has to be registered and allocated to NET operators (carbon credits registration); NET carbon registered in the credits system has to be prevented from re-entering the atmosphere (permanent storage).

Besides the techno-economic questions, the success of biomass-based control of the CO_2 concentration in the atmosphere strongly depends on the time required for the options to be in place and to effectively contribute to reaching the emissions reduction goals, e.g. “2030” and “2050”. Calculation models describing the time dependent processes of the BET and the NET option have been developed allowing the quantification of the effect achieved with biomass-based control of the CO_2 concentration in the atmosphere.

2 Bioenergy substituting for fossil energy

A model describing the time dependent carbon flows and the resulting changes in the carbon reservoirs in atmosphere and biosphere has been developed allowing the quantification of the carbon emissions reduction achieved by BET systems replacing fossil reference systems. Two kinds of biomass are considered as feedstock: purpose-grown biomass and by-product biomass.

2.1 The carbon flow model

As an indicator the time dependent parameter “carbon neutrality” (CN) is used. CN is defined as the difference between accumulated carbon emissions of the fossil reference system (if it would not have been replaced) and the bioenergy system divided by the carbon emissions of the fossil reference system (*Schlamadinger et al. 1995*). CN typically ranges between 0 (no emission reduction) and 1 (complete reduction). The functional relationships of the carbon flows per unit of useful energy in an energy plant when biomass fuels (bio) are substituted for fossil fuels (ref) are shown in Box 1. The influencing parameters depend on the characteristics of the biomass feedstock:

- Time delay: resulting from the time dependency of re-growth (feedstock: purpose-grown biomass) or avoided decay (feedstock: by-product biomass)
- Carbon intensity (CE): energy yield per unit of carbon
- Secondary effects (U): upstream processes for feedstock preparation, land use change

Analytical descriptions of the time dependent input functions will generally not be available. Therefore the time integration is achieved by summing up the time series of distinct (e.g. annual) values.

2.2 Example calculations

Example calculations show that emission reduction achieved with BET using forest based material is delayed up to several decades while using annual or short rotation crops and some biogenic waste fractions results in time delays of a few years. Following the example calculation of CN (Figure 1) the effects of parameter variations are shown in Figures 2 to 6 describing the characteristics of CN for different operational modes of the energy plant.

Figure 1 – Basic functions for the definition of Carbon Neutrality

For the example of logging residues substituting for coal the accumulated fossil carbon emissions C_{ref} and the net accumulated biomass carbon emissions C_{bio} are shown. The resulting CN reaches 0.8 after 45 years and is leveling off after 80 years at 0.9. The typical development of CN (negative values at the beginning of operation, staying below 1.0 beyond 100 years) results from the fact that the carbon efficiency (CE) of coal typically is higher than that of logging residues and the upstream emissions (U) of logging residues are assumed to be higher than those of coal.

Figure 2 – Effect of carbon efficiency

The different shapes of CN are the result of different carbon efficiency of fossil fuels and biomass (logging residues). The CE values in tC/TJ used in the Figure are: 30 for logging residues, 26 for coal, 20 for fuel oil and 15 for natural gas. With these values the biomass option emits more carbon during the first 5 (coal), 8 (oil) and 20 (gas) years when it enters a phase with annual emissions lower than the respective fossil options. After 50 years of operation the effect of different carbon efficiencies becomes small with CN staying below 1.0 for the reasons explained in Figure 1.

Figure 3 – Effect of upstream emissions

The upstream emissions originate from fuel production and upgrading to achieve the required feedstock properties. In the case of biomass (U_{bio}) the production step includes land-use changes which may be necessary to assure the continued operation of any non-energy conversion system whose feedstock input was diverted to the bioenergy system. The time between the upstream emissions U and the fuel combustion emissions 1/CE in the energy plant is typically in the order of one to two years. Thus, the emissions U and 1/CE in the calculation of c(t) (Box 1) are assumed to take place at the same time at $\tau = 0$. The values of U as percentages of 1/CE are assumed to vary between 0% and 10% for the reference (coal) and biomass (logging residues) case. The 0%/0% assumption (i.e. no upstream emissions for both fuels) results in CN reaching 1.0.

Figure 4 – Effect of the regrowth period length

In the case of purpose-grown biomass the characteristic of the carbon neutrality CN depends on the length of the biomass re-growth period. Typical examples for biomass substituting for coal are shown in Figure 4: Agricultural crops with 1 year, energy crops with 7 to 20 years and forest harvest with 70 years.

Figure 5 – Effect of decay period length

In the case of by-product biomass the characteristic of the carbon neutrality CN depends on the length of the biomass decay period. Typical examples for decaying biomass substituting for coal are: Residues from the agro-food and pulp&paper production with 1 year; harvesting, sawmill and manufacturing residues with 15 years; out-of-use wood products and demolition wood with 70 years.

Figure 6 – Increasing bioenergy capacity

Energy and climate policy goals usually include growth rates for renewable energy capacities within a certain time frame, e.g. to replace a certain amount of fossil capacities by a certain point in time. In the case of bioenergy this means that increasing the share of bioenergy capacities through installation of additional plants will result in an "accumulation" of the time delays associated with each individual plant leading to an extension of the overall time delay for the emissions reduction. Thus, the resulting "accumulated" CN curve is flatter than the curve for one plant. Figure 6 shows the situation for logging residues substituting for coal when one additional plant is added each year for 40 years.

Most carbon emissions reduction strategies specify reduction goals (amount, target date; e.g. the "1.5/2°C by 2050 goal"). The results of the examples show that some BET plants put in operation during the past decades or planned for the future may not provide the expected contribution to meeting CO_2 emissions reduction goals.

3 Biomass-based negative emission technologies (NET)

An overall characterization of NET options may be the intention of transferring the carbon removed from "natural" permanent stores (fossil fuels reservoirs) to "artificial" permanent stores on the earth's surface, thereby avoiding the build-up of CO_2 in the atmosphere. The three conditions for the success of biomass-based NET (additionality, carbon credit registration, permanent storage) require the establishment of new biomass plantations managed like forests for wood production (production forests) as illustrated in two examples.

3.1 Example 1: Increasing the size of the carbon stock in production forests

An increase of the carbon stock in forests may be realized through improved management of the existing production forests (fertilisation, decreasing or avoiding thinning, or lengthening rotation periods for forests below the maximum sustainable yield period) and the establishment of additional production forest areas *(Erb et al. 2018; Pingoud et al. 2018)*. Assuring the C stock increase and the wood harvest in the additional areas to remain constant requires implementation of specific management practices within the commercial operations (harvesting, replanting and wood supply management) of the "improved" and the additional production forest area. Figure 7 shows C pools and the flow between them for the case of increasing the C stock in the global production forest (164 GtC on 2236 Mha - *Pan et al. 2011*) by 10%. This would reduce the carbon content of the atmosphere (approx. 800 GtC) by 2% resulting in a reduction of the CO_2 concentration in the atmosphere (currently around 410 ppm) by approx. 8 ppm. The requirement of permanent storage of the 16 GtC may be met by the owner/operator through assuring "permanent operation" of the additional production forest. Economic losses resulting from this obligation would have to be compensated by a "carbon credit system" which would need to be established at the beginning of the operation.

Besides the questions around improving the forest management and/or the availability of additional forest areas an economic operation of the enlarged production forest capacities seems to be unlikely within the time horizon discussed for the stabilization of the atmospheric CO_2 concentration. In particular since maintaining the operation of the existing production forests would further extend the time horizon.

3.2 Example 2: Sequestering carbon in additional biomass plantations combined with permanent carbon storage

NET forest plantations outside and independent of existing production forests have similar requirements regarding establishing and accounting as described for Example 1; the difference lies in the treatment of mature trees. The requirement of permanent storage would be fulfilled by harvesting and burying the trees (Scholz and Hasse 2008) or other methods of permanently storing the carbon (e.g. producing and burying biochar with secondary benefits is under investigation) as shown in Figure 8. Such a scheme will have no revenues from any industrial source and consequently will need a financing scheme from outside the forest-wood sector.

4 Conclusions

Both options for a biomass-based control of the CO_2 concentration in the atmosphere (bioenergy technologies and negative emissions technologies) have limited benefits due to the time dependence of biomass growth and decay. For most biomass types it will take several decades from the start of projects to reaching their planned effectiveness. In addition the negative emissions technologies options require funding for implementation and operation of permanent storage capacities since reduced (Example 1) or no (Example 2) revenues are to be expected from the additional forest-wood operations. This means that for projects to be started during the next few years, it cannot be expected that the CO_2 concentration in the atmosphere will be stabilized or even reduced by biomass-based control at the point in time considered necessary, e.g. around 2050.

5 References

Erb et al. 2018: *Karl-Heinz Erb, Thomas Kastner, Christoph Plutzar, Anna Lisa S. Bais, Nuno Carvalhais, Tamara Fetzel, Simone Gingrich, Helmut Haberl, Christian Lauk, Maria Niedertscheider, Julia Pongratz, Martin Thurner, Sebastiaan Luyssaert, 2018. Unexpectedly large impact of forest management and grazing on global vegetation biomass. Nature, 553, 73-76 doi: 10.1038/*

Pan et al. 2011: *Pan, Y.; Birdsey, R. A.; Fang, J.; Houghton, R.; Kauppi, P. E.; Kurz, W. A.; Phillips, O. L.; Shvidenko, A.; Lewis, S. L.; Canadell, J. G.; Ciais, P.; Jackson, R. B.; Pacala, S. W.; McGuire, A. D.; Piao, S.; Rautiainen, A.; Sitch, S.; Hayes, D. 2011. A large and persistent carbon sink in the world's forests. Science. 333: 988-993, 2011*

***Pingoud et al. 2018**: Pingoud, K.; Ekholm, T.; Sievänen, R.; Huuskonen, S.; Hynynen, J. 2018. Trade-offs between forest carbon stocks and harvests in a steady state. A multi-criteria analysis. Journal of Environmental Management. 210: 96-103.*

***Schlamadinger et al. 1995**: B. Schlamadinger, J. Spitzer, G. H. Kohlmaier, W. Lüdeke; Carbon Balance of Bioenergy from Logging Residues; Biomass and Bioenergy, Vol. 8, no. 4, 1995*

Scholz and Hasse 2008: *Scholz, F., Hasse, U.; Permanent wood sequestration: The solution to the carbon dioxide problem; ChemSusChem 1/5: pages 381-384, 2008*

Box 1: Functional relationships of the carbon flows per unit of useful energy in an energy plant when biomass fuels (bio) are substituted for fossil fuels (ref)

$CN(t) = [C_{ref}(t) – C_{bio}(t)]/C_{ref}(t)$	*carbon neutrality after operation time t*
where	
$C_{ref}(t) = \int c_{ref}(t)dt$	*accumulated carbon emissions of the reference system after operation time t*
$C_{bio}(t) = \int c_{bio}(t)dt$	*accumulated carbon emissions of the bioenergy system after operation time t*
$c_{ref}(t) = U_{ref}(t) + 1/CE_{ref}(t)$	*carbon flux of the fossil reference system (including upstream fuel production) per unit of useful energy at time t*
$c_{bio}(t) = U_{bio}(t) + 1/CE_{bio}(t) – \sum c_r(t) + \sum c_a(t) – \sum c_e(t)$	*carbon flux of the bioenergy system (including upstream fuel production) at time t (Case 1, purpose-grown biomass)*
$c_{bio}(t) = U_{bio}(t) +1/CE_{bio}(t) – \sum c_d(t) – \sum c_e(t)$	*carbon flux of the bioenergy system (including upstream fuel production) at time t (Case 2, by-product biomass)*
$CE_{bio/ref}(t)$	*carbon efficiency of fossil or biomass fuels (amount of end-use energy produced from one unit of combusted carbon emitted)*
$U_{bio/ref}(t)$	*upstream (typically fossil) carbon emissions from fuel production per unit of combusted carbon emitted (including emissions from land-use change in the case of biomass fuels)*

Subscripts of carbon fluxes c(t):

d = avoided decay
r = regrowth
e = enhanced secondary growth (if stored permanently)
a = reduced absorption

Analytical descriptions of the functions $c_{ref}(t)$ and $c_{bio}(t)$ will generally not be available. For calculating the examples in this paper the time integration $\int dt$ has been replaced by the sum of the time series of distinct (e.g. annual) values. The summation $\sum$ refers to the contributions to the fluxes to (+) and from (–) the atmosphere at time t as they develop from the processes d, r, e and a after biomass fuel combustion prior to time t, e.g. at time $t – \tau$, where τ is the time elapsed since the combustion. The growth and decay related emissions and absorptions $c_d(\tau)$, $c_r(\tau)$, $c_e(\tau)$ and $c_a(\tau)$ are expressed as fractions of the combustion emissions $1/CE_{bio}(t)$ and are required input parameters. The technology and feedstock related parameters CE(t) and the upstream emissions U(t) are input parameters as well.

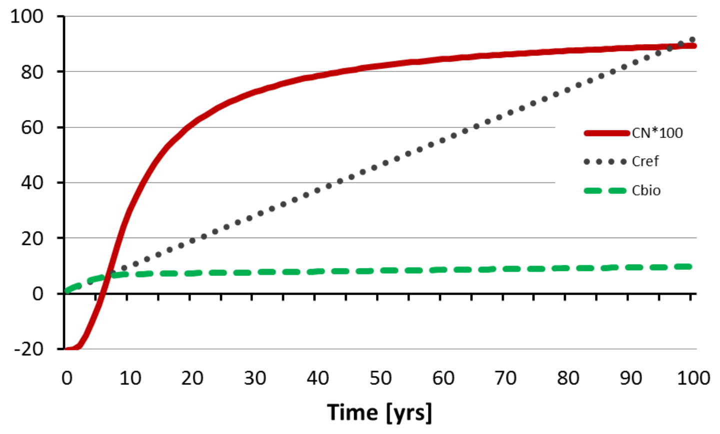

Figure 1: Functions for the definition of CN

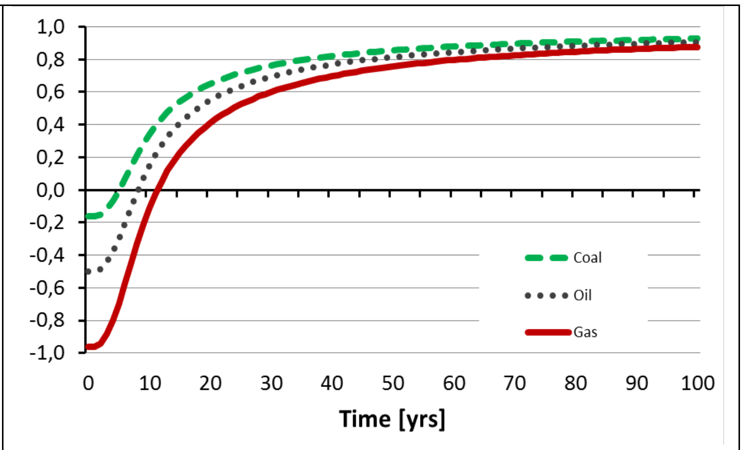

Figure 2: Effect of carbon efficiency CE

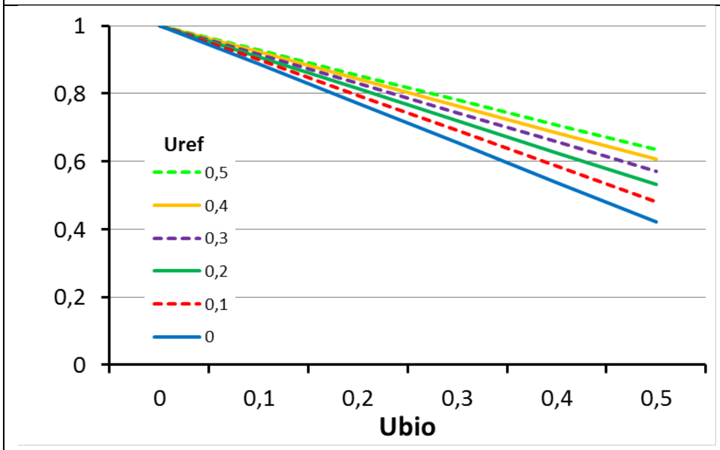

Figure 3: Effect of upstream emissions U

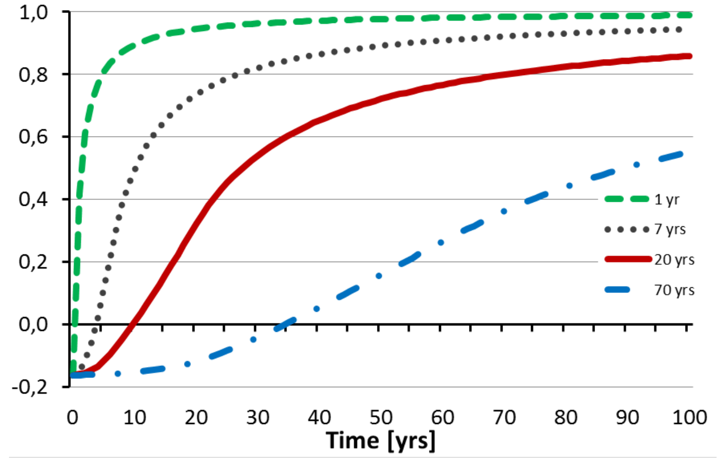

Figure 4: Effect of the regrowth period length c_r

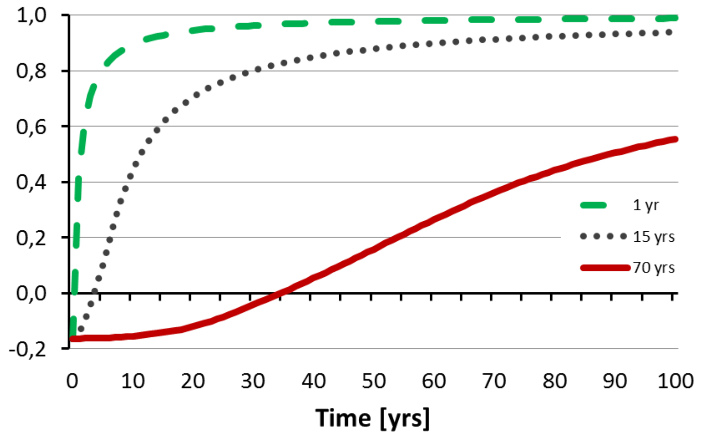

Figure 5: Effect of the decay period length c_d

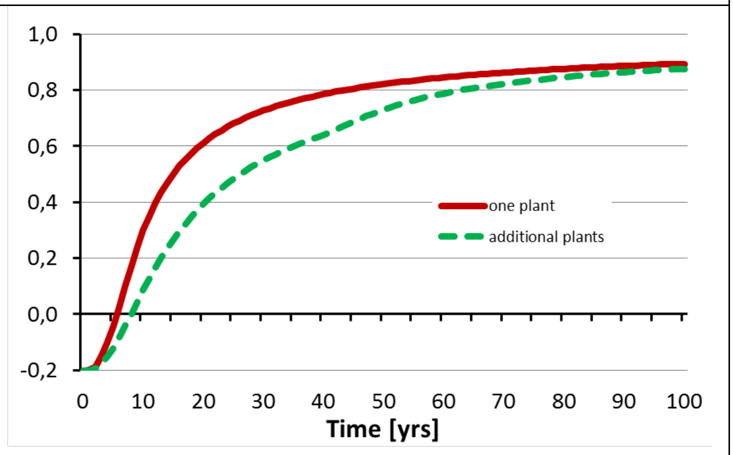

Figure 6: Increasing bioenergy capacity (one additional plant per year for 40 years)

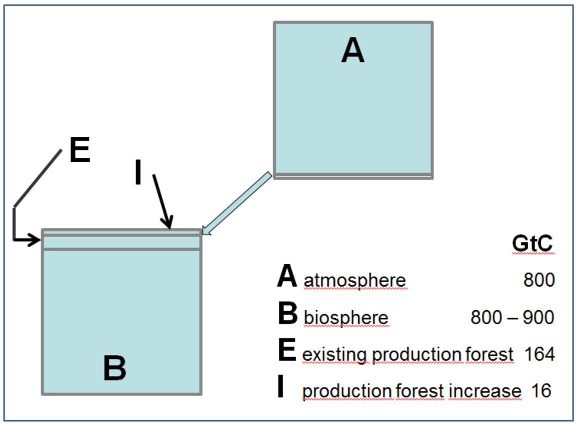

Figure 7: Increasing size and/or carbon density of the production forest and permanently maintaining the additional operation

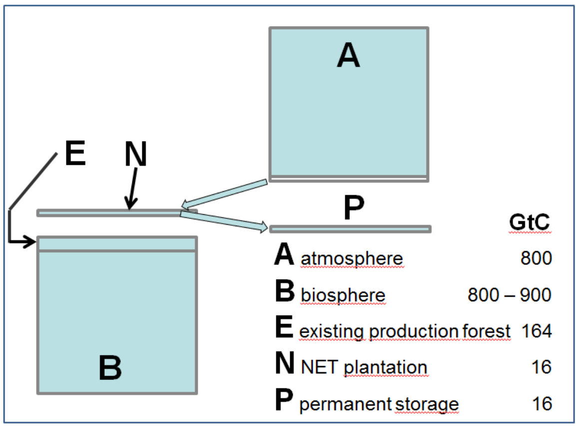

Figure 8: NET forest plantations outside and independent of existing production forests with a permanent storage of the harvested wood