IEooc_Application4_Exercise6:

Bioenergy and biomaterials from a life cycle perspective

Goal: *Get familiar with the carbon intensity of different energy carriers (orders of magnitude), understand the concept of distributing upfront emissions on the subsequently produced output, break-even emissions, and the computation of global warming impacts of emissions from a system at different times. ('dynamic GHG accounting').*

This exercise only considers GHG. Biodiversity and economic aspects of land conversion are highly relevant but are not studied here.

First, make yourself familiar with some fundamental calculations, data sources, and indicators for different fuels and materials:

1.1) How much CO_2 is emitted when combusting 1 l (litre) of diesel (or gasoline)?
1.2) How large is the volume (standard conditions) of natural gas (in gaseous form) that contains the same energy (lower heating value) as one litre of diesel?
1.3) How large is the mass of dry wood that contains the same energy (lower heating value) as one litre of diesel?
1.4) How much carbon is contained in 1 m^3 of dry wood (hard wood and soft wood)?

Interpret your results!

Hint: Some of the parameters needed for part 1 can be found on:

https://en.wikipedia.org/wiki/Energy_content_of_biofuel

https://en.wikipedia.org/wiki/Energy_density

In the second part, we consider how the GHG emissions from land use change are factored into the calculations of life cycle (field to tank) GHG emissions for biofuels. Land use change emissions occur, for example, when pristine forest is clear-cut to make space for palm oil plantations in tropical regions.

The supply chain emissions ('well to tank' and 'field to tank') of fossil (oil-based) diesel and palm oil diesel are roughly 0.087 kg CO_2-eq/MJ fuel combusted for fossil diesel and 0.015 kg CO_2-eq/MJ fuel combusted for palm oil diesel, respectively [1]. The latter value already shows that palm-oil-based diesel has a much lower carbon footprint than fossil diesel, but this number does not contain the emissions from land use change yet! Land use change emissions occur both instantaneously, when the original forest biomass is harvested for fuel wood or burned, and gradually, through decomposition of harvest residues and soil carbon stocks. In LCA standard practice, these emissions are aggregated into a single number and then allocated to the subsequently produced biofuel as land-use change emissions. For this approach, the time horizon over which the allocation happens is a crucial parameter and subjective/normative assumption that needs to be transparently stated.

For the palm-oil-based biodiesel studied, an ecoinvent dataset for Malaysia is used that reports total land use change GHG emissions of 270 t of CO_2-eq due to forest conversion [2]. The annual yield of palm fruit bunches (dry mass) is 13240 kg/ha (kilogram per hectare), which is already averaged over years with different productivity, taking into account years with low or zero productivity, e.g., right after planting the oil palms [2]. For producing 1 kg of biodiesel, 4.24 kg of palm fruit bunches (dry mass) are required [2]. Tailpipe emissions from biodiesel combustion are not accounted for, as they are assumed to be climate-neutral due to the short rotation period of palm fruits.

Tasks:

2.1) How large are the field-to-tank GHG emissions of the palm-oil-based biodiesel (per MJ) if the total land use change GHG emissions are distributed over the future output (assuming constant average output in the future)?

a) for an allocation time horizon of 30 years (by 2050) and

b) for a time horizon of 80 years (by 2100)?

2.2) How long must the allocation time horizon be chosen for the palm-oil-based biodiesel to become

a) as carbon intensive as the fossil diesel

b) 50% as carbon intensive as the fossil diesel

c) 33% as carbon intensive as the fossil diesel

Interpret your results!

References for part 2:

[1] Source: ecoinvent 3.2 via: Frederick Hatherly. A Comparative LCA Investigating the Environmental Impacts of the Biological and Fossil Feedstocks of Germany's B7 Diesel-Blend, Indecol Freiburg, 2019

Accessible via http://www.blog.industrialecology.uni-freiburg.de/index.php/2019/04/25/zur-klima-und-landnutzungsbilanz-von-dieselkraftstoff-b7/

[2] ecoinvent 3.6: palm fruit bunch production | palm fruit bunch | Cutoff, U, MY (Malaysia), UUID 3da1d67d-3141-37f2-9c1b-4f5414a3c902

The third part of this exercise introduces the accounting of carbon emissions and sequestration that are distributed over the life cycle of a product. For example, when a forest gradually sequesters CO_2 after a logging impact or when woody biomass is stored in form of a construction material before being burned for energy recovery. The life cycle of the forest product starts with the moment it is harvested from the forest (process 1) and then either used as material (modelled as carbon flow F_12(t=0) to process 2) or used as energy carrier (modelled as carbon flow F_13(0) to process 3) (Fig. 1). After a certain use time T, the wood used as material is discarded (modelled as carbon flow F_23(0) to process 3). All inflows to process 3 (energy recovery) are emitted back to the atmosphere (wood burning) within the same accounting period.

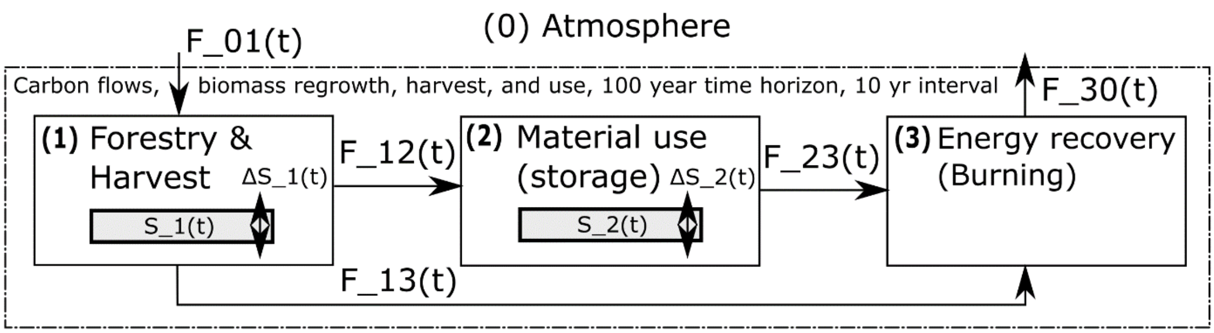

Figure 1: System definition for the life cycle of a wood-based product with either immediate use as energy carrier or use as material, followed by energy recovery. To keep calculations simple, the system is modelled in time steps of 10 years. The large boxes represent the three processes, the light grey boxes in the processes symbolize the carbon stocks in the processes, and the arrows on top of the grey boxes the carbon stock changes.

Here, we describe the harvesting and processing/use/energy recovery of a certain amount of wood with a carbon content of 2.73 tons, which corresponds to exactly 10 tons of CO_2. In **scenario (a)** the wood is sent directly to energy recovery via F_13. In **scenario (b)**, the wood is used as material for 50 years, whereupon it is sent to energy recovery.

After harvest, a new tree is planted and eventually, it will contain the same amount of carbon as the one that was cut in year 0. The following stylistic regrowth model shall be used here for F_01(t).

Table 1: Forest carbon uptake F_01(t) in tons C, t years after the harvest of 1 ton of carbon. This function models the regrowth of biomass harvested at t=0.

t	0	10	20	30	40	50	60	70	80	90	100
F_01(t)	0	0.05	0.1	0.2	0.3	0.2	0.1	0.05	0	0	0

Carbon emitted to the atmosphere will not stay there forever, but will be distributed between atmosphere, oceans, and biosphere in the subsequent years. The decay of atmospheric CO_2 following a pulse emission at t=0, C(t), is given by the so-called Bern carbon cycle-climate model using a background CO_2 concentration of 378 ppm (equation 1), (Levasseur et al., 2010):

$$C(t) = a_0 + a_1 \cdot \exp(-t/T_1) + a_2 \cdot \exp(-t/T_2) + a_3 \cdot \exp(-t/T_3) \qquad (1)$$

With a_0 = 0.217, a_1 = 0.259, a_2 = 0.338, a_3 = 0.186, τ_1 = 172.9 yr, τ_2 = 18.51 yr, and τ_3 = 1.186 yr.

This equation applies to all CO_2 flows to the atmosphere, fossil and biogenic. It is also used to model the effect of removing CO_2 from the atmosphere, e.g., via biomass growth (photosynthesis).

Next to the energy and material-energy scenarios a and b, a fossil comparison **scenario (c)** for 10 tons of fossil CO_2 at time t=0 and a reference **scenario (d)** for 1 ton of fossil CO_2 at time t=0 are considered. The latter will be used to calculate a CO_2 equivalent. The following tasks are given:

3.1) Create a tabular overview of the carbon exchange of the system in Figure 1 with the atmosphere (flows F_01(t) and F_30(t)) for scenarios a and b. Use CO_2 as mass unit and the time steps 0, 10, 20, …, 90, and 100 years. Show that the system is life cycle carbon neutral for both scenarios a and b, i.e., that the cumulative sum of flows F_01(t) and F_30(t) is 0.

3.2) Compute the values of the Bern carbon cycle model (equation 1) for the time steps 0, 10, 20, …, 90, and 100 years. We will use these values as averages for the different time intervals later on.

3.3) Calculate the CO_2 in the atmosphere after time t from biomass combustion (F_30(t)), tons, cases a and b. Calculate also the CO_2 'missing' in the atmosphere as a result of biomass regrowth (F_01(t)), time t since harvest, tons, cases a+b. Here, the carbon uptake in each time period causes a 'negative peak' as described by equation 1, and the different responses for the carbon update in each time period need to be summed up!

3.4) Calculate the net CO_2 in the atmosphere after time t from biomass combustion, in tons, for the wood harvest scenarios a) and b) as well as the net CO_2 in the atmosphere after time t for the two fossil reference cases c) and d). These results are proportional to the momentary global warming contribution of the product system at time t.

3.5) Calculate the cumulative CO_2 in atmosphere after time t for all four cases! These results are proportional to the cumulative global warming contribution of the product system between time 0 and time t.

3.6) Calculate, as main indicator, the cumulative contribution to global warming of the three scenarios a, b, and c as multiples of the warming contribution of the fossil CO_2 pulse emission of 1 ton (scenario d), over a time horizon of 100 years. This indicator is the global warming potential with a time horizon of 100 years (GWP100). It is defined as in equation 2, where the square brackets […] indicate the concentration of CO_2 in the atmosphere, measures in parts per billion (ppb), or simplified as measured in kg or tons, as the volume of the atmosphere is the same for both nominator and denominator.

$$GWP100(Scenario) = \frac{\sum_{t=0}^{t=100} [CO_{2\_scenario}(t)]}{\sum_{t=0}^{t=100} [CO_{2\_fossil}(t)]} \quad (2)$$

Interpret your results!

Taking into account the timing of GHG emissions becomes more and more common in LCA and is crucial for correctly assessing and comparing systems that involve material use and cascading. For more info, please check out the following papers:

(Levasseur et al., 2010)

(Cherubini and Strømman, 2011)

(Guest et al., 2013)

(Breton et al., 2018)

References for part 3:

Breton, C., Blanchet, P., Amor, B., Beauregard, R., Chang, W.S., 2018. Assessing the climate change impacts of biogenic carbon in buildings: A critical review of two main dynamic approaches. Sustain. 10.

Cherubini, F., Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresour. Technol. 102, 437–451.

Guest, G., Cherubini, F., Strømman, A.H., 2013. Global Warming Potential of Carbon Dioxide Emissions from Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life. J. Ind. Ecol. 17, 20–30.

Levasseur, A., Lesage, P., Margni, M., Deschenes, L., Samson, R., 2010. Considering Time in LCA : Dynamic LCA and Its Application to Global Warming Impact Assessments. Environ. Sci. Technol. 44, 3169–3174.