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Bioenergy

Simple use of biomass fuel (combustion of wood logs for heat).

Bioenergy is energy made from biomass or biofuel. Biomass is any organic material which has absorbed sunlight and stored it in the form of chemical energy. Examples are wood, energy crops and waste from forests, yards, or farms.[1] Since biomass technically can be used as a fuel directly (e.g. wood logs), some people use the terms biomass and biofuel interchangeably. More often than not, the word biomass simply denotes the biological raw material the fuel is made of. The word biofuel is usually reserved for *liquid* or *gaseous* fuels, used for transportation. The U.S. Energy Information Administration (EIA) follows this naming practice.[2]

The IPCC (Intergovernmental Panel on Climate Change) defines bioenergy as a renewable form of energy.[3] Researchers have disputed that the use of forest biomass for energy is carbon neutral.[4][5]

Contents

Biomass

Wood and wood residues is the largest biomass energy source today. Wood can be used as a fuel directly or processed into pellet fuel or other forms of fuels. Other plants can also be used as fuel, for instance corn, switchgrass, miscanthus and bamboo.[6] The main waste feedstocks are wood waste, agricultural waste, municipal solid waste, and manufacturing waste. Upgrading raw biomass to higher grade fuels can be achieved by different methods, broadly classified as thermal, chemical, or biochemical:

Thermal conversion processes use heat as the dominant mechanism to upgrade biomass into a better and more practical fuel. The basic alternatives are torrefaction, pyrolysis, and gasification, these are separated mainly by the extent to which the chemical reactions involved are allowed to proceed (mainly controlled by the availability of oxygen and conversion temperature).[7]

Many **chemical conversions** are based on established coal-based processes, such as the Fischer-Tropsch synthesis.[8] Like coal, biomass can be converted into multiple commodity chemicals.[9]

Biochemical processes have developed in nature to break down the molecules of which biomass is composed, and many of these can be harnessed. In most cases, microorganisms are used to perform the conversion. The processes are called anaerobic digestion, fermentation, and composting.[10]

Biofuel

Based on the source of biomass, biofuels are classified broadly into two major categories:[11]

Sugarcane plantation to produce ethanol in Brazil

First-generation biofuels are made from *food* sources grown on arable land, such as sugarcane and corn. Sugars present in this biomass are fermented to produce bioethanol, an alcohol fuel which serve as an additive to gasoline, or in a fuel cell to produce electricity. Bioethanol is made by fermentation, mostly from carbohydrates produced in sugar or starch crops such as corn, sugarcane, or sweet sorghum. Bioethanol is widely used in the United States and in Brazil. Biodiesel is produced from the oils in for instance rapeseed or sugar beets and is the most common biofuel in Europe.

Second-generation biofuels utilize *non-food*-based biomass sources such as perennial energy crops and agricultural residues/waste. The feedstock used to make the fuels either grow on arable land but are byproducts of the main crop, or they are grown on marginal land. Waste from industry, agriculture, forestry and households can also be used for second-generation biofuels, using e.g. anaerobic digestion to produce biogas, gasification to produce syngas or by direct combustion. Cellulosic biomass, derived from non-food sources, such as trees and grasses, is being developed as a feedstock for ethanol production, and biodiesel can be produced from left-over food products like vegetable oils and animal fats.

Power production compared to other renewables

To calculate land use requirements for different kinds of power production, it is essential to know the relevant surface power production densities. Vaclav Smil estimates that the average lifecycle surface power densities for biomass, wind, hydro and solar power production are 0.30 W/m^2, 1 W/m^2, 3 W/m^2 and 5 W/m^2, respectively (power in the form of heat for biomass, and electricity for wind, hydro and solar).[12] Lifecycle surface power density includes land used by all supporting infrastructure, manufacturing, mining/harvesting and decommissioning. Van Zalk et al. estimates 0.08 W/m^2 for biomass, 0.14 W/m^2 for hydro, 1.84 W/m^2 for wind, and 6.63 W/m^2 for solar (median values, with none of the renewable sources exceeding 10 W/m^2). Fossil gas has the highest surface density at 482 W/m² while nuclear power at 240 W/m² is the only high-density *and* low-carbon energy source.[13] The average human power consumption on ice-free land is 0.125 W/m² (heat and electricity combined),[14] although rising to 20 W/m² in urban and industrial areas.[15]

Plants with low yields have lower surface power density compared to plants with high yields. Additionally, when the plants are only partially utilized, surface density drops even lower. This is the case when producing liquid fuels. For instance, ethanol is often made from sugarcane's sugar content or corn's starch content, while biodiesel is often made from rapeseed and soybean's oil content.

Smil estimates the following densities for liquid fuels:

Ethanol

Wheat fields in the USA.

- Winter wheat (USA) 0.08 W/m² [16]
- Corn 0.26 W/m² (yield 10 t/ha) [17]
- Wheat (Germany) 0.30 W/m² [16]
- *Miscanthus x giganteus* 0.40 W/m² (yield 15 t/ha) [18]
- Sugarcane 0.50 W/m² (yield 80 t/ha wet) [19]

Jet fuel

- Soybean 0.06 W/m² [19]
- Jathropa (marginal land) 0.20 W/m² [19]
- Palm oil 0.65 W/m² [19]

Biodiesel

- Rapeseed 0.12 W/m² (EU average)[20]
- Rapeseed (adjusted for energy input, the Netherlands) 0.08 W/m² [21]
- Sugar beets (adjusted for energy input, Spain) 0.02 W/m² [21]

Eucalyptus plantation in India.

Combusting *solid* biomass is more energy efficient than combusting liquids, as the whole plant is utilized. For instance, corn plantations producing solid biomass for combustion generate more than double the amount of power per square metre compared to corn plantations producing for ethanol, when the yield is the same: 10 t/ha generates 0.60 W/m² and 0.26 W/m² respectively.[22]

Oven dry biomass in general, including wood, miscanthus[23] and napier[24] grass, have a calorific content of roughly 18 GJ/t.[25] When calculating power production per square metre, every t/ha of dry biomass yield increases a plantation's power production by 0.06 W/m².[a] Consequently, Smil estimates the following:

- Large-scale plantations with pines, acacias, poplars and willows in temperate regions 0.30–0.90 W/m² (yield 5–15 t/ha)[26]
- Large scale plantations with eucalyptus, acacia, leucaena, pinus and dalbergia in tropical and subtropical regions 1.20–1.50 W/m² (yield 20–25 t/ha) [26]

In Brazil, the average yield for eucalyptus is 21 t/ha (1.26 W/m²), but in Africa, India and Southeast Asia, typical eucalyptus yields are below 10 t/ha (0.6 W/m²).[27]

FAO (Food and Agriculture Organization of the United Nations) estimate that forest plantation yields range from 1 to 25 m^3 per hectare per year globally, equivalent to 0.02–0.7 W/m^2 (0.4–12.2 t/ha):[b]

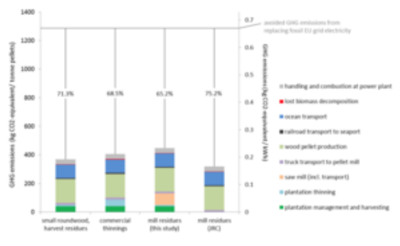
- Pine (Russia) 0.02–0.1 W/m^2 (0.4–2 t/ha or 1–5 m^3)[b]
- Eucalyptus (Argentina, Brazil, Chile and Uruguay) 0.5–0.7 W/m^2 (7.8–12.2 t/ha or 25 m^3)[b]
- Poplar (France, Italy) 0.2–0.5 W/m^2 (2.7–8.4 t/ha or 25 m^3)[b]

Smil estimate that natural temperate mixed forests yield on average 1.5–2 dry tonnes per hectare (2–2,5 m^3, equivalent to 0.1 W/m^2), ranging from 0.9 m3 in Greece to 6 m^3 in France).[28] IPCC provides average net annual biomass *growth* data for natural forests globally. Net growth varies between 0.1 and 9.3 dry tonnes per hectare per year, with most natural forests producing between 1 and 4 tonnes, and with the global average at 2.3 tonnes. Average net growth for plantation forests varies between 0.4 and 25 tonnes, with most plantations producing between 5 and 15 tonnes, and with the global average at 9.1 tonnes.[29]

As mentioned above, Smil estimates that the world average for wind, hydro and solar power production is 1 W/m^2, 3 W/m^2 and 5 W/m^2 respectively. In order to match these surface power densities, plantation yields must reach 17 t/ha, 50 t/ha and 83 t/ha for wind, hydro and solar respectively. This seems achievable for the tropical plantations mentioned above (yield 20–25 t/ha) and for elephant grasses, e.g. miscanthus (10–40 t/ha), and napier (15–80 t/ha), but unlikely for forest and many other types of biomass crops. To match the world average for biofuels (0.3 W/m^2), plantations need to produce 5 tonnes of dry mass per hectare per year. When instead using the Van Zalk estimates for hydro, wind and solar (0.14, 1.84, and 6.63 W/m^2 respectively), plantation yields must reach 2 t/ha, 31 t/ha and 111 t/ha in order to compete. Only the first two of those yields seem achievable, however.

Yields need to be adjusted to compensate for the amount of moisture in the biomass (evaporating moisture in order to reach the ignition point is usually wasted energy). The moisture of biomass straw or bales varies with the surrounding air humidity and eventual pre-drying measures, while pellets have a standardized (ISO-defined) moisture content of below 10% (wood pellets)[c] and below 15% (other pellets).[d] Likewise, for wind, hydro and solar, power line transmission losses amounts to roughly 8% globally and should be accounted for.[e] If biomass is to be utilized for electricity production rather than heat production, note that yields has to be roughly tripled in order to compete with wind, hydro and solar, as the current heat to electricity conversion efficiency is only 30–40%.[30] When simply comparing surface power density without regard for cost, this low heat to electricity conversion efficiency effectively pushes at least solar parks out of reach of even the highest yielding biomass plantations, surface power density wise.[f]

Carbon neutrality for forest biomass



GHG emissions from wood pellet production and transport (Hanssen et al. 2017).[31]

IEA defines carbon neutrality and carbon negativity like so: «Carbon neutrality, or 'net zero,' means that any CO_2 released into the atmosphere from human activity is balanced by an equivalent amount being removed. Becoming carbon negative requires a company, sector or country to remove more CO_2 from the atmosphere than it emits.»[32] The actual carbon intensity of biomass varies with production techniques and transportation lengths. According to the EU, typical greenhouse gas emissions savings when replacing fossil fuels with wood pellets from forest residues is 77% when the transport distance is between 0 and 500 km, also 77% when the transport distance is between 500 and 2500 km, 75% when the distance is between 2500 and 10

000 km, and 69% when the distance is above 10 000 km. When stemwood is used, the savings change only marginally, from between 70 and 77%. When wood industry residues are used, savings increase to between 79 and 87%.[g]

Likewise, Hanssen et al. argue that greenhouse gas emissions savings from wood pellets produced in the US southeast and shipped to the EU is between 65 and 75%, compared to fossil fuels.[h] They estimate that average net GHG emissions from wood pellets imported from the USA and burnt for electricity in the EU amounts to approximately 0.2 kg CO_2 equivalents per kWh, while average emissions from the mix of fossil fuels that is currently burnt for electricity in the EU amounts to 0.67 kg CO_2-eq per kWh (see chart on the right). Ocean transport emissions amounts to 7% of the fossil fuel mix emissions per produced kWh (equivalent to 93 kg CO_2-eq/t vs 1288 kg CO_2/t).[33]

IEA Bioenergy estimates that in a scenario where Canadian wood pellets are used to totally replace coal use in a European coal plant, the specific emissions originating from ocean transport of the pellets, going from Vancouver to Rotterdam, amounts to approximately 2% of the plant's total coal-related emissions.[34]

More CO_2 from wood combustion than coal combustion

When combusted in combustion facilities with the same heat-to-electricity conversion efficiency, oven dry wood emits slightly less CO_2 per unit of heat produced, compared to oven dry coal.[i] However, many biomass combustion facilities are relatively small and inefficient, compared to the typically much larger coal plants. Further, raw biomass can have higher moisture content compared to some common coal types. When this is the case, more of the wood's inherent energy must be spent solely on evaporating moisture, compared to the drier coal, which means that the amount of CO_2 emitted per unit of produced heat will be higher.

Some research groups (e.g. Chatham House) therefore argue that «[...] the use of woody biomass for energy will release higher levels of emissions than coal [...].»[35]


Coal port in Russia.

How much «extra» CO_2 that is released depends on local factors. Some research groups estimate relatively low extra emissions. IEA Bioenergy for instance estimates 10%.[36] The bioenergy consultant group FutureMetrics argue that wood pellets with 6% moisture content emits 22% *less* CO_2 for the same amount of produced heat, compared to sub-bituminous coal with 15% moisture, when both fuels are combusted in facilities with the same conversion efficiency (here 37%).[j] Likewise, they state that «[...] dried wood at MC's [moisture content] below 20% have the same or less CO_2 emission per MMBTU [million British thermal units] as most coal. Wood pellets at under 10% MC result in less CO_2 emission than any coal under otherwise equal circumstances.»[37] (Moisture content in wood pellets is usually below 10%, as defined in the ISO standard 17225-2:2014.)[38] However, when raw wood chips are used instead (45% moisture content), this wood biomass emits 9% *more* CO_2 than coal in general, for the same amount of produced heat.[37] According to Indiana Center for Coal Technology Research, the coal type anthracite typically contains below 15% moisture, while bituminous contains 2–15%, sub-bituminous 10–45%, and lignite 30–60%.[39] The most common coal type in Europe is lignite.[40]

Other research groups estimate relatively high extra emissions. The Manomet Center for Conservation Sciences for instance, argue that for smaller scale utilities, with 32% conversion efficiency for coal, and 20-25% for biomass, coal emissions are 31% less than for wood chips.

Assumed moisture content for wood chips is 45%, as above. The assumed moisture content for coal is not provided.[41]

The IPCC (Intergovernmental Panel on Climate Change) put their «extra CO_2» estimates for biomass at roughly 16% extra for wood over coal in general, somewhere in the middle compared to the estimates above.[k]

Is the extra CO_2 from biomass a problem? IPCC argues that focusing on gross emissions misses the point, what counts is the net effect of emissions and absorption taken together: «Estimating gross emissions only, creates a distorted representation of human impacts on the land sector carbon cycle. While forest harvest for timber and fuelwood and land-use change (deforestation) contribute to gross emissions, to quantify impacts on the atmosphere, it is necessary to estimate net emissions, that is, the balance of gross emissions and gross removals of carbon from the atmosphere through forest regrowth [...].»[42]

IEA Bioenergy provide a similar argument: «It is incorrect to determine the climate change effect of using biomass for energy by comparing GHG emissions at the point of combustion.»[36] They also argue that «[...] the misplaced focus on emissions at the point of combustion blurs the distinction between fossil and biogenic carbon, and it prevents proper evaluation of how displacement of fossil fuels with biomass affects the development of atmospheric GHG concentrations.»[43] IEA Bioenergy conclude that the additional CO_2 from biomass «[...] is irrelevant if the biomass is derived from sustainably managed forests.»[36]

Wood pellet mill in Germany.

What is sustainable managed forests? The IPCC writes: «Sustainable Forest Management (SFM) is defined as 'the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems' [...]. This SFM definition was developed by the Ministerial Conference on the Protection of Forests in Europe and has since been adopted by the Food and Agriculture Organization [of the United Nations (FAO)].»[44] Further, IPCC writes: «Sustainable forest management can prevent deforestation, maintain and enhance carbon sinks and can contribute towards GHG emissions-reduction goals. Sustainable forest management generates socio-economic benefits, and provides fibre, timber and biomass to meet society's growing needs.»[45]

In the context of CO_2 mitigation, the key measure regarding sustainability is the size of the forest carbon stock. In a research paper for FAO, Reid Miner writes: «The core objective of all sustainable management programmes in production forests is to achieve a long-term balance between harvesting and regrowth. [...] [T]he practical effect of maintaining a balance between harvesting and regrowth is to keep long-term carbon stocks stable in managed forests.»[46]

Is the forest carbon stock stable? Globally, the forest carbon stock has decreased 0.9% and tree cover 4.2% between 1990 and 2020, according to FAO.[47] IPCC states that there is disagreement about whether the global forest is shrinking or not, and quote research indicating that tree cover has increased 7.1% between 1982 and 2016.[l] IPCC writes: «While above-ground biomass carbon stocks are estimated to be declining in the tropics, they are increasing globally due to increasing stocks in temperate and boreal forests [...].»[48]

Forest protection

Some research groups seem to want more than «just» sustainably managed forests, they want to realize the forests *full* carbon storage potential. For instance EASAC writes: «There is a real danger that present policy over-emphasises the use of forests in energy production instead of increasing forest stocks for carbon storage.»[49] Further, they argue that «[...] it is the older, longer-rotation forests and protected old-growth forests that exhibit the highest carbon stocks.»[50] Chatham House argues that old trees have a very high carbon absorption, and that felling old trees means that this large potential for future carbon absorption is lost. In addition they argue that there is a loss of soil carbon due to the harvest operations.[51]

Old-growth spruce forest in France.

Research show that old trees absorb more CO_2 than young trees, because of the larger leaf area in full grown trees.[52] However, the old forest (as a whole) will eventually stop absorbing CO_2 because CO_2 emissions from dead trees cancel out the remaining living trees' CO_2 absorption.[m] The old forest (or forest stands) are also vulnerable for natural disturbances that produces CO_2. The IPCC writes: «When vegetation matures or when vegetation and soil carbon reservoirs reach saturation, the annual removal of CO_2 from the atmosphere declines towards zero, while carbon stocks can be maintained (high confidence). However, accumulated carbon in vegetation and soils is at risk from future loss (or sink reversal) triggered by disturbances such as flood, drought, fire, or pest outbreaks, or future poor management (high confidence).»[53] Summing up, IPCC writes that «[...] landscapes with older forests have accumulated more carbon but their sink strength is diminishing, while landscapes with younger forests contain less carbon but they are removing CO_2 from the atmosphere at a much higher rate [...].»[54] Regarding soil carbon, the IPCC writes: «Recent studies indicate, that effects of forest management actions on soil C [carbon] stocks can be difficult to quantify and reported effects have been variable and even contradictory (see Box 4.3a).» Because the «current scientific basis is not sufficient», the IPCC will not currently provide soil carbon emission factors for forest management.[55]

Regarding the net climate effect of conversion from natural to managed forests, the IPCC argues that it can swing both ways: «SFM [sustainable forest management] applied at the landscape scale to existing unmanaged forests can first reduce average forest carbon stocks and subsequently increase the rate at which CO_2 is removed from the atmosphere, because net ecosystem production of forest stands is highest in intermediate stand ages (Kurz et al. 2013; Volkova et al. 2018; Tang et al. 2014). The net impact on the atmosphere depends on the magnitude of the reduction in carbon stocks, the fate of the harvested biomass (i.e. use in short – or long-lived products and for bioenergy, and therefore displacement of emissions associated with GHG-intensive building materials and fossil fuels), and the rate of regrowth. Thus, the impacts of SFM on one indicator (e.g., past reduction in carbon stocks in the forested landscape) can be negative, while those on another indicator (e.g., current forest productivity and rate of CO_2 removal from the atmosphere, avoided fossil fuel emissions) can be positive. Sustainably managed forest landscapes can have a lower biomass carbon density than unmanaged forest, but the younger forests can have a higher growth rate, and therefore contribute stronger carbon sinks than older forests (Trofymow et al. 2008; Volkova et al. 2018; Poorter et al. 2016).»[44]

In other words, there is a tradeoff between the benefits of having a maximized forest carbon stock, not absorbing any more carbon, and the benefits of having a portion of that carbon stock «unlocked», and instead working as a renewable fossil fuel replacement tool. When put to work, this carbon is constantly replacing carbon in fossil fuels used in for instance heat production and baseload electricity production – sectors where it is un-economical or impossible to use intermittent power sources like wind or solar. Being a renewable carbon source, the unlocked portion keep cycling back and forth between forests and forest products like lumber and wood pellets. For each cycle it replaces more and more of the fossil based alternatives, e.g. cement and coal.

FAO researcher Reid Miner argues that the «competition» between locked-away and unlocked forest carbon is won by the unlocked carbon: «In the long term, using sustainably produced forest biomass as a substitute for carbon-intensive products and fossil fuels provides greater permanent reductions in atmospheric CO_2 than preservation does.»[56]

Summing up the above, IEA Bioenergy writes: «As the IPCC has pointed out in several reports, forests managed for producing sawn timber, bioenergy and other wood products can make a greater contribution to climate change mitigation than forests managed for conservation alone, for three reasons. First, the sink strength diminishes as conservation forests approach maturity. Second, wood products displace GHG-intensive materials and fossil fuels. Third, carbon in forests is vulnerable to loss through natural events such as insect infestations or wildfires, as recently seen in many parts of the world including Australia and California. Managing forests can help to increase the total amount of carbon sequestered in the forest and wood products carbon pools, reduce the risk of loss of sequestered carbon, and reduce fossil fuel use.»[57]


Plantation forest in Hawaii.

The IPCC further suggest that the possibility to make a living out of forestry incentivize sustainable forestry practices: «[...] SFM [sustainable forest management] aimed at providing timber, fibre, biomass and non-timber resources can provide long-term livelihood for communities, reduce the risk of forest conversion to non-forest uses (settlement, crops, etc.), and maintain land productivity, thus reducing the risks of land degradation [...].»[54] Further: «By providing long-term livelihoods for communities, sustainable forest management can reduce the extent of forest conversion to non-forest uses (e.g., cropland or settlements) (high confidence).»[58]

The National Association of University Forest Resources Programs agrees: «Research demonstrates that demand for wood helps keep land in forest and incentivizes investments in new and more productive forests, all of which have significant carbon benefits. [...] Failing to consider the effects of markets and investment on carbon impacts can distort the characterization of carbon impacts from forest biomass energy.»[59]

Favero et al. focus on the potential future increase in demand and argues: «Increased bioenergy demand increases forest carbon stocks thanks to afforestation activities and more intensive management relative to a no-bioenergy case [...] higher biomass demand will increase the value of timberland, incentivize additional investment in forest management and afforestation, and result in greater forest carbon stocks over time».[60]

Possibly strengthening the arguments above, data from FAO show that most wood pellets are produced in regions dominated by sustainably managed forests. Europe (including Russia) produced 54% of the world's wood pellets in 2019, and the forest carbon stock in this area increased from 158.7 to 172.4 Gt between 1990 and 2020. Likewise, North America produced 29% of the worlds pellets in 2019, while forest carbon stock increased from 136.6 to 140 Gt in the same period. Carbon stock decreased from 94.3 to 80.9 Gt in Africa, 45.8 to 41.5 Gt in South and Southeast Asia combined, 33.4 to 33.1 Gt in Oceania,[n] 5 to 4.1 Gt in Central America, and from 161.8 to 144.8 Gt in South America. Wood pellet production in these areas combined was 13.2% in 2019.[o] Chatham House answers the above argument like so: «Forest carbon stock levels may stay the same or increase for reasons entirely unconnected with use for energy.»[61]

Carbon payback time

Some research groups still argue that even if the European and North American forest carbon stock is increasing, it simply takes too long for harvested trees to grow back. EASAC for instance argues that since the world is on track to pass by the agreed target of 1.5 degrees temperature increase already in a decade or so, CO_2 from burnt roundwood, which resides in the atmosphere for many decades before being re-absorbed, make it harder to achieve this goal. They therefore suggest that the EU should adjust its sustainability criteria so that only renewable energy with carbon payback times of less than 10 years is defined as sustainable,[p] for instance wind, solar, biomass from wood residues and tree thinnings that would otherwise be burnt or decompose relatively fast, and biomass from short rotation coppicing (SRC).[62] Chatham House agrees, and in addition argues that there could be tipping points along the temperature scale where warming accelerates.[q] Chatham House also argues that various types of roundwood (mostly pulpwood) is used in pellet production in the USA.[63]

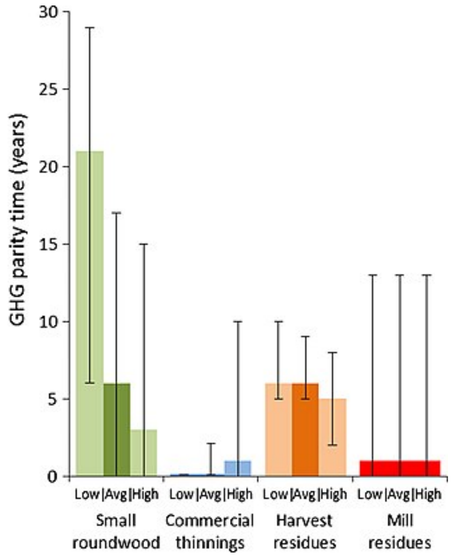
FutureMetrics argues that it makes no sense for foresters to sell sawlog-quality roundwood to pellet mills, since they get a lot more money for this part of the tree from sawmills. Foresters make 80-90% of their income from sawlog-quality roundwood (the lower and thicker straigth part of the tree stem), and only 10-15% from pulpwood, defined as a.) the middle part of mature trees (the thinner part of the stem that often bends a little, plus branches) and b.) tree thinnings (small, young trees cleared away for increased productivity of the whole forest stand.) This low-value biomass is mainly sold to pulp mills for paper production, but in some cases also to pellet mills for pellet production.[64] Pellets are typically made from sawmill residues in areas where there are sawmills, and from pulpwood in areas without sawmills.[r]

Chatham House further argue that almost all available sawmill residue is already being utilized for pellet production, so there is no room for expansion. For the bioenergy sector to significantly expand in the future, more of the harvested pulpwood must go to pellet mills. However, the harvest of pulpwood (tree thinnings) removes the possibility for these trees to grow old and therefore maximize their carbon holding capacity.[65] Compared to pulpwood, sawmill residues have lower net emissions: «Some types of biomass feedstock can be carbon-neutral, at least over a period of a few years, including in particular sawmill residues. These are wastes from other forest operations that imply no additional harvesting, and if otherwise burnt as waste or left to rot would release carbon to the atmosphere in any case.»[66]

An important presupposition for the «tree regrowth is too slow» argument is the view that carbon accounting should start when trees from particular, harvested forest stands are combusted, and not when the trees in those stands start to grow.[s] It is within this frame of thought it becomes possible to argue that the combustion event creates a carbon debt that has to be repaid through regrowth of the harvested stands.[t]

When instead assuming that carbon accounting should start when the trees start to grow, it becomes impossible to argue that the emitted carbon constitutes debt.[u] FutureMetrics for instance argue that the harvested carbon is not a debt but «[...] a benefit that was earned by 30 years of management and growth [...].»[67] Other researchers however argue back that «[...] what is important to climate policy is understanding the difference in future atmospheric GHG levels, with and without switching to woody biomass energy. Prior growth of the forest is irrelevant to the policy question [...].»[68] Undermining forester's income may backfire however, see above for IPCC's argument that forests which provide long-term livelihood for communities reduce the risk of forest conversion to non-forest uses.

Some researchers limit their carbon accounting to particular forest stands, ignoring the carbon absorption that takes place in the rest of the forest.[v] In opposition to this single forest stand accounting practice, other researchers include the whole forest when doing their carbon accounting. FutureMetrics for instance argue that the whole forest continually absorb CO_2 and therefore immediately compensate for the relatively small amounts of biomass that is combusted in biomass plants from day to day.[w] Likewise, IEA Bioenergy criticizes EASAC for ignoring the carbon absorption of forests as a whole, noting that there is no net loss of carbon if annual harvest do not exceed the forest's annual growth.[x]



Greenhouse gas parity times for wood-pellet electricity from different feedstocks (Hanssen et al. 2017.)[69]

IPCC argue along similar lines: «While individual stands in a forest may be either sources or sinks, the forest carbon balance is determined by the sum of the net balance of all stands.»[70] IPCC also state that the only universally applicable approach to carbon accounting is the one that accounts for both carbon emissions and carbon removals (absorption) for the whole *landscape* (see below). When the total is calculated, natural disturbances like fires and insect infestations are subtracted, and what remains is the human influence.[y] In this way, the whole landscape works as a proxy for calculating specifically human GHG emissions: «In the AFOLU [Agriculture, Forestry and Other Land Use] sector, the management of land is used as the best approximation of human influence and thus, estimates of emissions and removals on managed land are used as a proxy for anthropogenic emissions and removals on the basis that the preponderance of anthropogenic effects occurs on managed lands (see Vol. 4 Chapter 1). This allows for consistency, comparability, and transparency in estimation. Referred to as the Managed Land Proxy (MLP), this approach is currently recognised by the IPCC as the only universally applicable approach to estimating anthropogenic emissions and removals in the AFOLU sector (IPCC 2006, IPCC 2010).»[71]

Hanssen et al. notes that when comparing continued wood pellet production to a potential policy change where the forest instead is protected, most researchers estimate a 20–50 year carbon parity (payback) time range for the burnt wood pellets. But when instead comparing continued pellet production to the more realistic alternative scenarios of 1.) instead using all harvested biomass to produce paper, pulp or wood panels, 2.) quitting the thinning practice altogether (leaving the small trees alone, realizing more of their growth potential but at the same time reduce the growth potential of the bigger trees), and 3.) leaving the forest residue alone, so it is decomposed in the forest over time, rather than being burned almost immediately in power plants, the result is that carbon payback (parity) times for wood pellets drop to 0-21 years in all demand scenarios (see chart on the right). The estimate is based on the landscape rather than the individual forest stand carbon accounting practice.[72]

Short-term vs long-term climate benefits

Researchers from both sides agree that in the short term, emissions might rise compared to a no-bioenergy scenario. IPCC for instance states that forest carbon emission avoidance strategies always give a short-term mitigation benefit, but argue that the long-term benefits from sustainable forestry activities are larger:[70]

> Relative to a baseline, the largest short-term gains are always achieved through mitigation activities aimed at emission avoidance [...]. But once an emission has been avoided, carbon stocks on that forest will merely be maintained or increased slightly. [...] In the long term, sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual yield of timber, fibre, or energy from the forest, will generate the largest sustained mitigation benefit.

— IPCC 2007

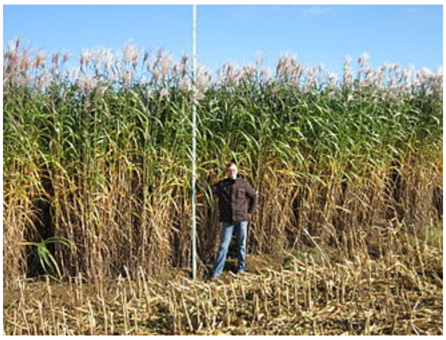
Similarly, addressing the issue of climate consequences for modern bioenergy in general, IPCC states: «Life-cycle GHG emissions of modern bioenergy alternatives are usually lower than those for fossil fuels […].»[73] Consequently, most of IPCC's GHG mitigation pathways include substantial deployment of bioenergy technologies.[74] Limited or no bioenergy pathways leads to increased climate change or shifting bioenergy's mitigation load to other sectors.[z] In addition, mitigation cost increases.[aa]

IEA Bioenergy also prioritize the long-term benefits: «Concern about near-term emissions is not a strong argument for stopping investments that contribute to net emissions reduction beyond 2030, be it the scaling-up of battery manufacturing to support electrification of car fleets, the development of rail infrastructure, or the development of biomass supply systems and innovation to provide biobased products displacing fossil fuels, cement and other GHG-intensive products. We assert that it is critical to focus on the global emissions trajectory required to achieve climate stabilization, acknowledging possible trade-offs between short- and long-term emissions reduction objectives. A strong focus on short-term carbon balances may result in decisions that make long-term climate objectives more difficult to meet.»[43] IEA states that «[…] the current rate of bioenergy deployment is well below the levels required in low carbon scenarios. Accelerated deployment is urgently needed to ramp up the contribution of sustainable bioenergy across all sectors […].»[75] They recommend a five-fold increase in sustainable bioenergy feedstock supply.[ab]

The National Association of University Forest Resources Programs agrees, and argues that a timeframe of 100 years is recommended in order to produce a realistic assessment of cumulative emissions: «Comparisons between forest biomass emissions and fossil fuel emissions at the time of combustion and for short periods thereafter do not account for long term carbon accumulation in the atmosphere and can significantly distort or ignore comparative carbon impacts over time. […] The most common timeframe for measuring the impacts of greenhouse gases is 100 years, as illustrated by the widespread use of 100-year global warming potentials. This timeframe provides a more accurate accounting of cumulative emissions than shorter intervals.»[76]

Carbon neutrality for energy crops

Like with forests, it is the total amount of CO_2 equivalent emissions and absorption together that determines if an energy crop project is carbon positive, carbon neutral or carbon negative. If emissions during agriculture, processing, transport and combustion are higher than what is absorbed, both above and below ground during crop growth, the project is carbon positive. Likewise, if total absorption over time is higher than total emissions, the project is carbon negative.



Miscanthus x giganteus energy crop, Germany.

Many first generation biomass projects are carbon positive (have a positive GHG life cycle cost), especially if emissions caused by direct or indirect land use change are included in the GHG cost calculation. The IPCC state that indirect land use change effects are highly uncertain, though.[ac] Some projects have higher total GHG emissions than some fossil based alternatives.[ad][ae][af] Transport fuels might be worse than solid fuels in this regard.[ag]

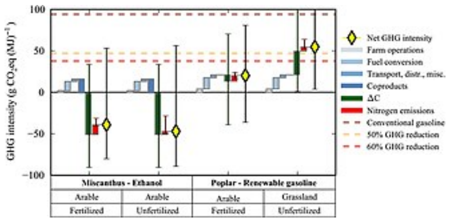
During plant growth, ranging from a few months to decades, CO_2 is re-absorbed by new plants.[77] While regular forest stands have carbon rotation times spanning many decades, short rotation forestry (SRF) stands have a rotation time of 8–20 years, and short rotation coppicing (SRC) stands 2–4 years.[78] Perennial grasses like miscanthus or napier grass have a rotation time of 4–12 months.

In addition to absorbing CO_2 and storing it as carbon in its above-ground tissue, biomass crops also sequester carbon below ground, in roots and soil.[ah] Typically, perennial crops sequester more carbon than annual crops because the root buildup is allowed to continue undisturbed over many years. Also, perennial crops avoid the yearly tillage procedures (plowing, digging) associated with growing annual crops. Tilling helps the soil microbe populations to decompose the available carbon, producing CO_2.[ai][aj]

Soil organic carbon has been observed to be greater below switchgrass crops than under cultivated cropland, especially at depths below 30 cm (12 in).[79] A large meta-study of 138 individual studies, done by Harris et al., revealed that second generation perennial grasses (miscanthus and switchgrass) planted on arable land on average store five times more carbon in the ground than short rotation coppice or short rotation forestry plantations (poplar and willow).[ak]

McCalmont et al. compared a number of individual European reports on Miscanthus x giganteus carbon sequestration, and found accumulation rates ranging from 0.42 to 3.8 tonnes per hectare per year,[al] with a mean accumulation rate of 1.84 tonne (0.74 tonnes per acre per year),[am] or 25% of total harvested carbon per year.[an] When used as fuel, greenhouse gas (GHG) savings are large—even without considering the GHG effect of carbon sequestration, miscanthus fuel has a GHG cost of 0.4–1.6 grams CO_2-equivalents per megajoule, compared to 33 grams for coal, 22 for liquefied natural gas, 16 for North Sea gas, and 4 for wood chips imported to Britain from the USA.[ao]

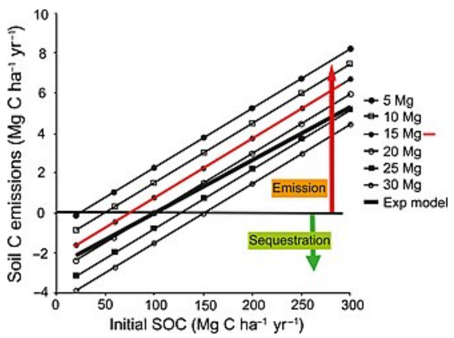
Likewise, Whitaker et al. argue that a miscanthus crop with a yield of 10 tonnes per hectare per year sequesters so much carbon below ground that the crop more than compensates for both agriculture, processing and transport emissions. The chart on the right displays two CO_2 negative miscanthus production pathways, and two CO_2 positive poplar production pathways, represented in gram CO_2-equivalents per megajoule. The bars are sequential and move up and down as atmospheric CO_2 is estimated to increase and decrease. The grey/blue bars represent agriculture, processing and transport related emissions, the green bars represents soil carbon change, and the yellow diamonds represent total final emissions.[ap]



Carbon negative (miscanthus) and carbon positive (poplar) production pathways.

Successful sequestration is dependent on planting sites, as the best soils for sequestration are those that are currently low in carbon. The varied results displayed in the graph highlights this fact.[aq] For the UK, successful sequestration is expected for arable land over most of England and Wales, with unsuccessful sequestration expected in parts of Scotland, due to already carbon rich soils (existing woodland) plus lower yields. Soils already rich in carbon includes peatland and mature forest.

Milner et al. further argue that the most successful carbon sequestration in the UK takes place below improved grassland.[ar] However, Harris et al. notes that since the carbon content of grasslands vary considerably, so does the success rate of land use changes from grasslands to perennial.[as] The bottom graphic displays the estimated yield necessary to achieve CO_2 negativity for different levels of existing soil carbon saturation. The higher the yield, the more likely CO_2 negativity becomes.



Relationship between above-ground yield (diagonal lines), soil organic carbon (X axis), and soil's potential for successful/unsuccessful carbon sequestration (Y axis). Basically, the higher the yield, the more land is usable as a GHG mitigation tool (including relatively carbon-rich land).

Environmental impact

Biodiversity and pollution

Gasparatos et al. reviews current research about the side effects of all kinds of renewable energy production, and argue that in general there is a conflict between "[...] site/local-specific conservation goals and national energy policy/climate change mitigation priorities [...]." The authors argue that for instance biodiversity should be seen as an equally "[...] legitimate goal of the Green Economy as curbing GHG emissions."[80] Oil palm and sugar cane are examples of crops that have been linked to reduced biodiversity.[81] Other problems are pollution of soil and water from fertiliser/pesticide use,[82] and emission of ambient air pollutants, mainly from open field burning of residues.[83]

The authors note that the extent of the environmental impact "[...] varies considerably between different biomass energy options."[81] For impact mitigation, they recommend "[...] adopting environmentally-friendly bioenergy production practices, for instance limiting the expansion of monoculture plantations, adopting wildlife-friendly production practices, installing pollution control mechanisms, and undertaking continuous landscape monitoring."[84] They also recommend "[...] multi-functional bioenergy landscapes."[84] Other measures include "[...] careful feedstock selection, as different feedstocks can have radically different environmental trade-offs. For example, US studies have demonstrated that 2nd generation feedstocks grown in unfertilized land could provide benefits to biodiversity when compared to monocultural annual crops such as maize and soy that make extensive use of agrochemicals."[84] Miscanthus and switchgrass are examples of such crops.[85]

Air quality

The traditional use of wood in cook stoves and open fires produces pollutants, which can lead to severe health and environmental consequences. However, a shift to modern bioenergy contribute to improved livelihoods and can reduce land degradation and impacts on ecosystem services.[at] According to the IPCC, there is strong evidence that modern bioenergy have «large positive impacts» on air quality.[86] When combusted in industrial facilities, most of the pollutants originating from woody biomass reduce by 97-99%, compared to open burning.[87] A study of the giant brown haze that periodically covers large areas in South Asia determined that two thirds of it had been principally produced by residential cooking and agricultural burning, and one third by fossil-fuel burning.[88]

BECCS

Bioenergy with carbon capture and storage (BECCS) is the process of extracting bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere.[89] The carbon in the biomass comes from the greenhouse gas carbon dioxide (CO_2) which is extracted from the atmosphere by the biomass when it grows. Energy is extracted in useful forms (electricity, heat, biofuels, etc.) as the biomass is utilized through combustion, fermentation, pyrolysis or other conversion methods. Some of the carbon in the biomass is converted to CO_2 or biochar which can then be stored by geologic sequestration or land application, respectively, enabling carbon dioxide removal and making BECCS a negative emissions technology.[90]

The IPCC Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), suggests a potential range of negative emissions from BECCS of 0 to 22 gigatonnes per year.[91] As of 2019, five facilities around the world were actively using BECCS technologies and were capturing approximately 1.5 million tonnes per year of CO_2.[92] Wide deployment of BECCS is constrained by cost and availability of biomass.[93][94]

See also

- Biochar

- Bioenergy in China
- Biofuel
- Biogas
- Jean Pain
- Pellet fuel
- Biomass energy with carbon capture and storage
- European Biomass Association

Notes

a. Cf. Smil's estimate of 0.60 W/m^2 for the 10 t/ha yield above. The calculation is: Yield (t/ha) multiplied with energy content (GJ/t) divided by seconds in a year (31 556 926) multiplied with the number of square metres in one hectare (10 000).

b. For yield estimates see FAO's "The global outlook for future wood supply from forest plantations" (http://www.fao.org/3/X8423E/X8423E08.htm#TopOfPage), section 2.7.2 – 2.7.3. Scot's pine, native to Europe and northern Asia, weighs 390 kg/m^3 (https://www.wood-database.com/scots-pine/) oven dry (moisture content 0%). The oven dry weight of eucalyptus species commonly grown in plantations in South America is 487 kg/m^3 (average of Lyptus (https://www.wood-database.com/lyptus/), Rose Gum (https://www.wood-database.com/rose-gum/) and Deglupta (https://www.wood-database.com/deglupta/)). The average weight of poplar species commonly grown in plantations in Europe is 335 kg/m^3 (average of White Poplar (https://www.wood-database.com/white-poplar/) and Black Poplar (https://www.wood-database.com/black-poplar/).

c. "The raw material for wood pellets is woody biomass in accordance with Table 1 of ISO 17225-1. Pellets are usually manufactured in a die, with total moisture content usually less than 10 % of their mass on wet basis." ISO (International Organization for Standardization) 2014a.

d. "The raw material for non-woody pellets can be herbaceous biomass, fruit biomass, aquatic biomass or biomass blends and mixtures. These blends and mixtures can also include woody biomass. They are usually manufactured in a die with total moisture content usually less than 15 % of their mass." ISO (International Organization for Standardization) 2014b.

e. Transmission loss data from the World Bank, sourced from IEA. The World Bank 2010.

f. Additionally, Smil estimates that newly installed photovoltaic solar parks reaches 7–11 W/m^2 in sunny regions of the world. Smil 2015, p. 191.

g. The estimates are for the "medium case" considered (case 2a); a pellet mill that uses wood for processing heat, but sources electricity from the grid. Estimates (for forest residue based pellets) reduce to 50–58% when fossil fuels is used for processing heat (case 1), but increase to 84-92% when electricity is sourced from a CHP biomass power plant (case 3a). See EUR-Lex 2018, p. Annex VI.

h. "[...] GHG emission reductions of wood-pellet electricity compared to fossil EU grid electricity are 71% (for small roundwood and harvest residues), 69% (for commercial thinnings) or 65% (for mill residues), as shown in more detail in Fig. S3. The GHG reduction percentage of wood-pellet electricity from mill residues was [...] 75% [...]." Hanssen et al. 2017, pp. 1415-1416.

i. See EPA 2020, p. 1. The emission factors are based on the higher heating value (HHV) of the different fuels. The HHV value reflects the actual chemical energy stored in the fuel, without taking moisture content into consideration. The fuel’s lower heating value (LHV) is the energy that remains after the necessary amount of energy has been spent to vaporize the fuel’s moisture (so that the fuel is able to reach the ignition point).

j. See FutureMetrics 2015a, pp. 1–2. Chatham House notes that modern CHP plants (Combined Heat and Power) achieve much higher efficiencies, above 80%, for both fossil fuels and biomass. Chatham House 2017, p. 16.

k. The individual emission rates are: Wood 112 000 kg CO2eq per TJ, anthracite 98 300, coking coal 94 600, other bituminous 94 600, sub-bituminous 96 100, lignite 101 000. IPCC 2006a, pp. 2.16–2.17.