Biogas Beats Bioethanol

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The purpose of all biofuel production is to harvest the energy provided by solar radiation and use it to displace fossil fuels and their associated pollution and greenhouse gas load. Liquid or gaseous biofuels can be generated from organic waste (food scraps, food production byproducts, agricultural waste, excrements), from algae, or by agricultural means. The latter has by far the greatest market share and is much more scalable. It involves using fertile land, planting energy crops (sugarcane, corn, grasses, fast-growing trees, and others), harvesting them, and then using physical, chemical and/or biological processing to extract the compounds that can be used for combustion processes: ethanol (C_2H_6O), butanol ($C_4H_{10}O$), natural gas (CH_4), hydrogen (H_2), as well as others. This agricultural production of biofuels is also the subject of this article. The numerical results reported on here were obtained one of our biogas plants located in central Germany, which was operated with a feedstock mixture of 25 tons of corn silage and 11 tons of cattle dung per day.

In order to utilize biofuels optimally we need to (1) achieve the highest possible energy yield per hectare of land, (2) generate the least harmful emissions during the production process, and (3) find the highest net energy ratio, i.e. the ratio of the biofuels' final energy content divided by the average fossil fuel energy input needed to generate the biofuel, integrated over the lifetime of the production equipment and facilities.

Let's first look at the scale of the annual net energy harvest that can be expected from a hectare of land covered with energy crops. The solar constant, the power delivered by solar radiation at perpendicular incidence at the top of Earth's atmosphere, is 1,400 W/m^2. However, atmospheric absorption and reflection prevents approximately half of the solar radiation to reach the ground. The day/night and seasonal cycles further reduce the annual mean insolation. Typical values for agricultural regions range between ~200 W/m^2 (e.g. Brazil, Southern USA, South-East Asia, sub-Saharan Africa) and ~100 W/m^2 (e.g. Canada, Central Europe, Russia). From this information, and knowing that 1 hectare = 10,000 m^2 and 1 year ~ 31.6 million seconds, we can easily obtain the total solar energy delivered annually to each hectare of land to range between $3\text{-}6\cdot 10^{13}$ J, i.e. 30,000 to 60,000 Giga-Joules.

Biofuels rely on energy crops, and these utilize photosynthesis to convert solar energy into plant mass, a process with typical overall efficiency of approximately 1% to 2%. This leaves only 300 to 1,200 Giga-Joules of energy that can be harvested from each hectare of land. Processing the energy crops after harvest takes further energy input and reduces the overall efficiency of the biofuels generation process significantly. Currently, corn-based bioethanol is able to deliver up to 80 Giga-Joules of energy per hectare. Future plans, yet to be realized, promise to perhaps double this yield to 160 Giga-Joules per hectare. Parts of the research program to achieve this goal are cellulosic bioethanol or cross-species gene implantation techniques.

However, there already is a better way to harvest solar energy from energy crops than chemical distillation into ethanol. This process is biological fermentation, producing biogas in an anaerobic digester. Biogas is an approximately 60%/40% mixture of methane and carbon dioxide. It can be combusted in gas engines to generate electricity, or it can be cleaned and liquefied to yield liquid natural gas (LNG), which can be used as transportation fuel. LNG has an almost identical caloric content per liter as ethanol, approximately 2/3 of that of gasoline.

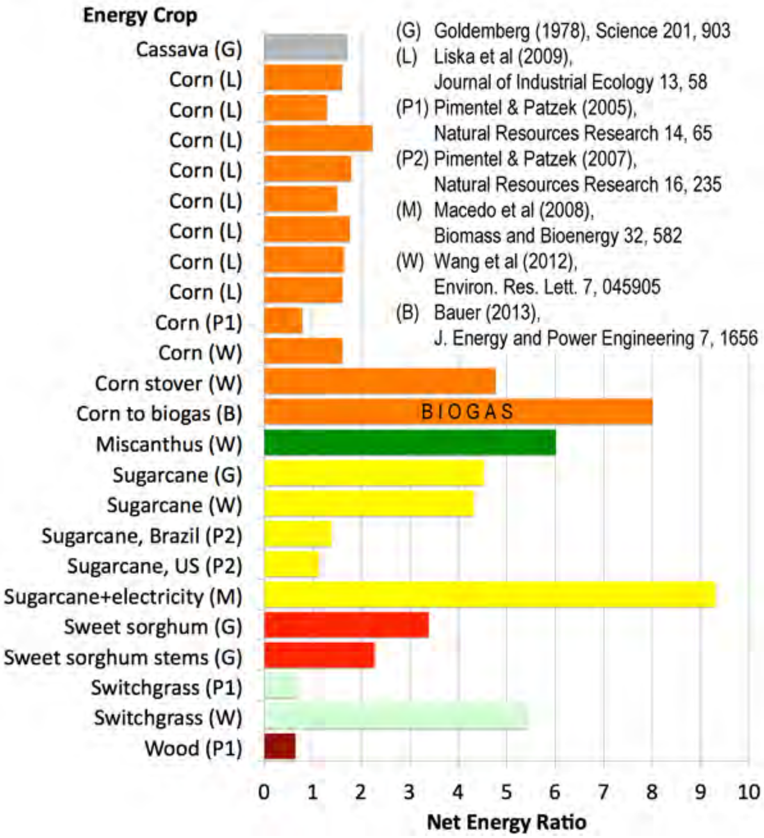
An example for a 1 MW anaerobic digester power plant fed with corn as well as animal excrements.

The biogas production plant shown in the photo is producing approximately 0.7 MW of electricity from 150 hectare of corn. It can operate at constant power output throughout every hour of the year. In order to do this, the primary fermenter needs to be fed twice per day with several tons of corn silage, which is stored onsite, and mixed with animal excrement. This corn silage is generated once a year during harvest time by shredding the corn and then storing it in large silos. The energy delivered by this biofuel conversion process is approximately 150 Giga-Joules per hectare. In the process of generating electricity the gas engines produce approximately the same amount of thermal energy, an additional 150 Giga-Joules per hectare. This thermal energy can be used for hot water production, district heating, or industrial processes. In other words, current biogas power plants are already achieving and exceeding the kinds of energy yields, which are the future goals of the bioethanol industry.

Our measurements indicate that it is possible to extract between three and four times more transportation fuel in form of LNG from each acre of corn via the process of biological fermentation than what is possible in form of ethanol production. The US Energy Information Agency reports that 54 billion liters of fuel ethanol were produced in the USA in 2014. If one would convert the same acreage of corn used in this process to LNG production, one could harvest at least an additional 100 billion gallons of transportation fuel.

What about the net energy ratio? There are many authors and researchers, who have compiled life cycle analyses for biofuel production processes and facilities to determine the total fossil fuel based energy that is needed. Diesel fuel to run the tractors used for anything from plowing the land to bringing home the harvest is a big contributor, as are herbicides and pesticides, artificial fertilizer, plant seeds, and possible chemical additives in the biofuel processing stages. But we also cannot forget that the farm equipment and the biofuel production facilities have a finite lifetime and thus contribute to the need for fossil fuel input.

The end product of a careful life cycle analysis is the net energy ratio, i.e. the ratio of the net energy content of the biofuel divided by the total fossil fuel input to produce it. Obviously, this ratio needs to be above 1 in order for the biofuel production to have any positive contribution to climate change considerations. And the larger the net energy ratio is, the more valuable the process outcome is.



Net energy ratio for the production ethanol for several different energy crops (corn: orange, sugarcane: yellow, grasses: green, …), as reported by different research groups for different facilities, compared to the net energy ratio achieved by our biogas plant.

The graph shows a compilation of this net energy ratio for bioethanol production from different energy crops in different facilities and using different energy crops, as reported by a representative sample of the peer-reviewed literature. They are compared to the net energy ratio of 8.0 achieved by our corn-based biogas plant. One can clearly see that biogas production from corn has a huge advantage over ethanol production from corn. The only process with a higher reported net energy ratio, 9.3, is the combination of ethanol production from sugarcane with electricity production from the burning of bagasse (which is the fibrous material left over after sugarcane is crushed to extract the juice).

We need to keep in mind that the net energy ratio of 8.0 we achieved for the process of corn to biogas to electricity is not as high as what could have been obtained, if we had cleaned and liquefied the methane in the biogas. This will be the subject of a future study. But it is interesting to estimate the expected range. The engines we use to convert biogas into electricity have an efficiency of 0.4. The latent heat of vaporization of methane is 510.8 kJ/kg, approximately 1% of the heat of combustion. Depending on the method used to remove CO_2 and other molecular compounds from the methane, we may expect a net energy ratio in the range of 15 to 20 for the process of creating LNG from anaerobic digestion of corn.

It is straightforward to burn methane in car engines without major modifications, a technology which is already firmly established. Finally, biologically generated methane can be transported very easily by using the existing pipeline infrastructure for natural gas, and long-time storage is also not presenting large engineering challenges. Ethanol, by contrast, is strongly hygroscopic.

It is time to rethink the US strategy of using corn-based ethanol as the major biofuel and instead switch to biogas methane generated from anaerobic digestion of the same energy crops: biogas beats bioethanol!

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