

Title: Net Energy Ratio and Greenhouse Gas Analysis
of a Biogas Power Plant

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Abstract

We present a net energy life cycle analysis and greenhouse gas analysis for a 1.45 MW (0.71 MW electrical) biogas power plant operating with a 70% corn silage and 30% cow dung feedstock after its initial five years of operation. We find a ratio of 8.0 for the total output electrical energy divided by the total input energy from fossil fuels. We obtain a net efficiency of 1.2% of converting solar energy into electricity and usable heat (0.6% electricity). Only 16 g CO₂ per kWh are generated in the process. If all greenhouse gases are considered, our process even actively reduces the total greenhouse gas load on the atmosphere. In terms of producing transportation biofuels our process provides 3.8 times more yield per hectare than bioethanol generation.

INTRODUCTION

The carbon-dioxide concentration in our atmosphere is rising steadily.¹ Approximately 15 billion tons of CO₂ are added annually, predominantly from the burning of fossil fuels. Caused by this increase in anthropogenic greenhouse gases is a rise in the average global temperature and an increase of the acidity of the oceans. We cannot predict with certainty what the effects of the rise of atmospheric greenhouse gases and associated global warming will be, but it seems prudent to avoid finding out. To this end many countries have begun large investments in alternative power sources, such as wind turbines, geothermal power plants, bioethanol production facilities, and solar-thermic or photovoltaic installations, among others. Generating the approximately 16 TW of current global power consumption requires use of all available technologies.²

In order to have a real positive impact, however, we have to make sure that the alternative means of power production deployed to mitigate greenhouse gas emissions have a positive net energy output and that they provide an effective net reduction in greenhouse gas emissions over their lifetime. This analysis must take into account the initial construction, plant and equipment maintenance, procurement of fuels, disposal of waste, and energy and water use during operation.

Among the biomass-based technologies, ethanol produced from corn has received the largest influx of investments. However, it is far from clear how much this mode of generating transportation fuels reduces net greenhouse gas emissions, if at all,³⁻⁶ and the same can be said for other energy plant feed stocks for bioethanol or biodiesel production.⁵ Recent results on consolidated bioprocessing of AFEX-pretreated corn stover to ethanol and hydrogen in a microbial electrolysis cell⁷ show great promise of enhanced energy recovery, but a complete net energy and greenhouse gas analysis has not yet been performed.

Here we report on the energy and greenhouse gas economy of another method to turn renewable biomass into electricity, heat, and/or transportation fuel: a biogas power plant. Biogas is mixture of carbon dioxide and methane (typically 60% by volume), which can be burned in high-efficiency engines/generators to produce electricity. The basic principle to produce the biogas is the same that is employed in a cow's stomach: anaerobic fermentation. Suitable feed stocks for this type of power plant can be a wide variety of organic matter such as energy plants (corn, switchgrass, sugarcane, ...), restaurant food waste, lawn clippings, leaves, organic waste from water treatment plants, and even animal excrements. For the specific example presented here we used a 70/30 mixture of shredded corn (the entire plant, not just the cob) and cow dung.

MATERIALS AND METHODS

We present an energy and greenhouse gas analysis of a biogas power plant located in the central part of Germany, just East of Frankfurt. The plant is operated by CPM Biogas GmbH & Co KG and has been in continuous operation for the past five years.

The corn is grown on 150 hectares of land, with an average yield of 60 metric tons of corn (33-35% dry substance) per hectare. For comparison, the USDA reports an average of 19.3 tons/acre (= 47.7 tons/hectare) yields for 2010. The same data source lists the corn grain yield as 12.0 tons/hectare, using 70 kg/bushel for corn. It is very important to note that we do not use any artificial irrigation and rely only on rain to provide water. Even more important for the energy and greenhouse gas accounting is that we do not use artificial fertilizer, but only spread the fermentation residue on the fields, which provides enough nutrients (N,P,K,Ca) to prevent soil deterioration and sustain plant growth.

In central Germany the growing season for corn extends from April to October, at which point the corn is shredded and stored in large silos. Approximately 25 metric tons of corn silage per day is mixed with 11 tons of cow dung and inserted into an anaerobic digester, where the biogas is produced. We find that an average of 100 m³/ton of biogas are produced from the cow dung, and 240 m³/ton of biogas are produced from the corn silage. Our biogas production is enhanced by approximately 10-20% with the aid of an enzyme/sugar mixture, of which we add 15 kg to the feed stock mixture every day. Each day approximately 30 tons of solid/liquid mixture fermentation residue is produced in this process, which is a high-quality organic fertilizer.

The calculated electricity outputs were compared to and verified by the meter readings of the electricity delivered to the grid. The calculated energy input and diesel consumption were verified against the annual diesel fuel bills.

Fossil-Fuel Based Energy Inputs

A large energy input into our process is the diesel fuel for the tractors and harvesters. From our fuel purchase records we find that 71 liters of fuel per hectare are needed to prepare the soil, seed the corn, spray herbicides, and harvest the corn. Almost 50% of this total is used by the shredder/harvester operation alone. We account separately for the transportation of the shredded corn from the fields to the power plant and the fertilizer and herbicides from the plant to the fields. For the tractors and trailers used, a typical average is a load of 16 tons. This means that on average 9.4 round trips between the fields and the power plant are required per hectare each year. If the fields were arranged in a circle around the power plant, the mean distance between the fields and the power plant would be 0.87 km, but we find that a realistic value is approximately 2 km. Using a typical number of 0.55 liter of diesel per km for the tractors, this translates into 20.6 liters/hectare of diesel consumed annually for transportation. It has to be noted that the amount of diesel

fuel spent on transportation is proportional to the square root of the total acreage of the fields and thus proportional to the power output of the farm. This implies that for a power plant of approximately 10 times bigger size the transportation fuel would dominate the energy input calculations. Another 3,000 liters per year are used for the operation of the feeder tractor. Thus the total diesel fuel consumed in growing, harvesting, and transporting the corn feed stock and in the plant operation is close to 17,000 liters. With a heat of combustion for diesel fuel of 10.4 kWh/liter this means that this part of the operation consumes almost 180 MWh annually.

The plant itself uses a variety of electric motors for pumps, actuators, compressors, valves, and controls. Collectively these consume 8% of the total produced electricity, almost 500 MWh per year. In addition, we use approximately 2% of the produced thermal energy to keep the fermenter at a constant optimal operating temperature, close to body temperature of a cow. This amounts to 130 MWh/year.

The total labor involved is a half-time person for day-to-day plant operation and routine maintenance, 6 people working full-time during the harvest for one week, and 11 hours/hectare for a total of 0.79 man-years spent on working the cornfields. Thus it takes approximately 1.4 people to provide the entire labor for this operation. Since a person eats approximately 2500 food calories per day, he or she consumes approximately 1 MWh in food each year. Therefore if one only counts the calories from food as energy input, the total annual energy costs in labor are a vanishingly small 1.4 MWh.

To estimate the total wear and tear on our farm equipment we follow the numbers produced by Pimentel and Patzek,⁵ which amounts to 1.18 MWh/hectare, for a total of 180 MWh of energy cost per year.

Corn seeds amount to an energy input of 0.60 MWh/hectare, for a total of 92 MWh. We use approximately 3 liters of herbicides/pesticides per hectare. The price per liter for these chemicals is approximately 20 times that of diesel fuel; and so we budget, as an upper limit, each liter of herbicide the same as 20 liters of diesel fuel in our energy and greenhouse gas calculations. Therefore an upper limit for our annual energy consumption from herbicides/pesticides is 95 MWh. Finally, we add 15 kg of enzymes additives daily to our plant feedstock to enhance methane production. The price of 1 kg of this mixture is 3 times that of 1 liter of diesel fuel, which means a contribution of 171 MWh debit to our energy calculations.

RESULTS AND DISCUSSION

Our biogas power plant uses the corn harvested from 150 hectares of land and produces an average of 7100 m³ of biogas (60/40 mixture of CH₄ and CO₂) per day, which means that we generate approximately 4200 m³ of methane per day. This

methane, approximately 1100 metric tons/year, could be liquefied and be used as a transportation fuel, or it could be pipelined to the end user. However, in our present mode of operation we burn the biogas in high-efficiency gas engines (40% electric and 42% thermal coefficient of efficiency) to generate electricity and co-generate heat. Since the heat of combustion (lower heating value) for methane is 50 MJ/kg, this means that our plant generates approximately 17 MWh of electricity and approximately 18 MWh of heat per day, which means that our plant produces 6200 MWh of electricity per year and 6500 MWh of heat.

Obviously, the conversion of solar energy, carbon dioxide, and water in the process of the growth of the corn provides the input energy for our power production process. But we have to perform a careful life-cycle analysis to determine what the total annual energy input from other, predominantly fossil fuel, sources is.

Net Energy Ratio

If we add up all of the external energy inputs listed in the Materials and Methods section, we find a total of 715 MWh used in the entire operation per year. The annual net energy production, after subtraction of the heat and electricity produced for the operation of the plant, is 12,100 MWh. The net energy output-to-input ratio is therefore 16.9 for our plant. If one only counts the net produced electricity of 5700 MWh (after subtraction of the 500 MWh of electricity used for the plant operation) and leaves out the co-produced heat, then the output-to-input ratio is still 8.0. This compares very favorably to the net energy ratios for bioethanol, which range from⁵ below 1.0 up to⁸ 2.2. Our net energy ratio is higher than the highest estimates of 5.4 for bioethanol from switchgrass,⁹ and as high as the highest estimates of bioethanol from sugarcane.¹⁰ These latter numbers are, however, strongly contested, and other authors¹¹ arrive at net energy ratios as low as 1.38.

In Fig. 1 we provide a visual summary of all energy inputs (right column) and net energy outputs (left and center columns).

Solar Conversion Efficiency

The total annual solar energy received by the central part of Germany¹² is 1.05 MWh/m². The length of the corn-growing season is almost 5 months, during which the fields receive approximately 60% of the annual solar energy. This amounts to 800 GWh of solar energy for our entire land area used for growing the corn. Therefore the integrated net solar efficiency of our biogas power plant is 1.2%, and the net electrical conversion efficiency is 0.6%.

Greenhouse Gases

Diesel fuel combustion produces 2.68 kg of CO₂ per liter of diesel.¹³ The total CO₂ production of our operation from diesel fuel consumption is therefore 45.4 tons. The fermentation enzymes (68.5 tons), herbicides/pesticides (23.7 tons), seeds, farm equipment wear and tear (46.4 tons) also add significant amount of CO₂, for a total of 184 tons of CO₂ produced by our entire plant operation per year. The net CO₂ produced from the burning of the methane from the fermentation of the corn silage

is zero, and so our total CO₂ output is 16 g per kWh of produced energy. This number compares very favorably to ~1 kg of CO₂ produced per kWh from the burning of coal in power plants, for example. It makes our power plant close to carbon-neutral.

However, if we examine the entire greenhouse gas emission, then the picture that emerges is even more positive. We use 11 tons of cow dung per day, each of which releases 100 m³ of methane.¹⁴ Used as a conventional agricultural fertilizer, a large fraction of this methane would escape into the atmosphere, between 30% and 70%, depending on spreading techniques, storage times, and composition of the dung. In our operation we capture this methane and effectively turn it into CO₂. This prevents between 50 and 120 tons of methane from entering the atmosphere each year. The global warming potential of methane is 25 times that of carbon dioxide (100 year time horizon). If we budget a savings of 25 tons of CO₂ for each ton of CH₄ sequestered in this way, then we arrive at a net CO₂ output of between -100 g and -250 g per kWh of produced energy. If we consider only a 20-year horizon, then the global warming potential of CH₄ is approximately 70 times that of CO₂, and our numbers are even better by a factor of ~3. Independent of the assumptions and scenarios used, the conclusion is that the entire biogas plant operation not only does not contribute to the greenhouse gas problem, but that it provides an actual net mitigation!

Transportation Fuels

If transportation fuel production is the ultimate goal, then our present plant is able to produce 2.6 million liters of liquid methane per year. Pimentel^{5,15} calculates that one can generate 1 liter of ethanol from 2.69 kg of corn grain. Using our corn silage production of 60 tons/hectare and our corn grain production of 12 tons/hectare, the same area used by us would yield 0.68 million liters of ethanol. This number of ~4,500 L/ha is consistent with the range of yields reported⁸ between 4,000 and 5,600 L/ha.

Since the heat of combustion per liter for methane and for ethanol are nearly identical, our process produces approximately 3.8 times more usable transportation fuel per hectare than bioethanol production. A highly fuel-efficient compact car uses 6 liters of gasoline per 100 km,¹⁶ which would correspond to 9 liter of methane or ethanol with suitably retrofitted engines. The annual methane output of our plant would allow to one drive this car for 29 million km. (Converting a car with a gasoline engine to one that can drive on methane is fairly inexpensive, around \$3,000.) If we were to feed the annual electricity produced by our plant in a compact electric car (55 km driving distance per 10 kWh charge), one could drive it for 35 million km. This number exceeds earlier estimates based on simple combustion-of-biofuels scenarios,^{17,18} while at the same time keeping particulate emissions at far smaller levels.

Our five-year experiment shows that biogas production through biological fermentation in an anaerobic digester is a viable way to convert solar energy into electricity and/or transportation fuel, that this process is much more efficient than the production of bioethanol, and that it is close to carbon-neutral and even actively reduces the total greenhouse gas load on the atmosphere.

Economic and Environmental Impact

Finally, electricity and methane are much easier to transport than ethanol and can easily utilize existing transportation networks (power lines and natural gas pipelines). Since our entire plant infrastructure can be recreated for approximately \$3-\$4 million, and since this initial investment can be recouped after approximately 4 years, any corn farm of >150 hectares in size can be converted into an independently owned power plant. Thus our approach is easily scalable to wherever corn is presently grown for the purpose of generating biofuels. Our results suggest that it is time to reexamine how one utilizes biomass, and in particular corn, for energy and/or liquid biofuels production. In the USA alone, corn-ethanol production is projected to reach 50 billion liters within the next five year.⁸ Our results suggest that one could harvest 190 billion liters of methane from the same land area. Since over 13 million hectares of former cropland are currently enrolled in the US Conservation Reserve Program,¹⁹ this area could be utilized for biofuels production without having an impact on food supply. With our process a large fraction of the USA's transportation fuel needs could be satisfied in a sustainable way.

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Figure Legends:

Fig. 1: Total annual energy inputs (right column) and net energy outputs (left: heat, center: electricity) of our biogas power plant.

