Energetics of cultivation: draft animals vs. combustion engines and the Haber process

Posted by Engineer-Poet on September 23, 2009 - 10:19am
Topic: Alternative energy
Tags: biofuel, biogas, biomass, energy balance, gasogene, haber process, pyrolysis oil [list all tags]

The energy use by the agricultural sector of the economy has been widely discussed and debated in the peak oil community. The amount of energy used directly at farms is not very large; typical claims for the fuel required to cover a field with a plow or other implement are in the range of one gallon of diesel per acre per pass. Assuming seeding, harvesting and 3 other passes per year, the total comes to approximately 750 MJ per acre per year. Nitrogen fertilizer applied at 200 pounds of nitrogen per acre would account for another 4600 MJ per acre[1]. Residues from many crops such as corn can supply over 20 GJ per acre and energy sources such as wood chips and fuel grasses are even more productive. Farming operations such as dairies have already become net exporters of energy as electricity. This suggests that even a mechanized farm can be self-sufficient in energy, and "fast crash" doom scenarios involving the collapse of farming are not very likely.

---

1 Farming before powered machinery

Before self-powered farm machinery, there were draft animals. They were slow to reproduce and train, and often dangerous to work. They were fed using the one quarter to one third of land fallowed as pasture at any given time. Some grain (such as oats) was also needed as supplemental feed.

Despite use of animal manures as fertilizer, the yields of the time were not very high. 40 bushels of corn (maize) per acre were typical. Combined with fallowed acreage, net productivity was a fraction of today's averages. Productivity was also low; a double-furrow plow pulled by 3 or 4 horses could only plow 2.5 acres per day.

2 The transition to modern practices: steam tractors

The change to steam gave several major improvements. Steam engines could use any fuel which would burn in the fire box; it did not have to be suitable for animal food. They also did not have to be "fed" when not working. Last, the productivity went up radically; one man on a steam tractor could plow 25 to 40 acres per day.

The thermal efficiency of open-cycle steam engines is quite low, roughly 5%. Guessing from the efficiency of modern diesel engines, it would have taken perhaps 1.2 GJ of fuel to make one pass over an acre. This is about 180 pounds of firewood, or a considerably smaller amount of coal. Being able to plow several acres with the wood from one tree was a huge improvement over draft animals.

3 Internal combustion engines (ICEs) and their efficiency

Internal combustion engines are much more efficient than piston steam engines, as well as much more convenient to operate. Thermal efficiency of medium-speed diesel engines runs upwards of 40%, and low-speed marine diesels can top 50%. Internal combustion engines can also operate on biofuels, with handicaps which depend on the exact fuel fed to the engine.

4 Homegrown ICE fuel supplies

While current vehicles and farm equipment are fairly finicky about their fuel, the generic ICE is quite adaptable. Spark-ignition ICEs can be run on everything from petroleum to ammonia to carbon monoxide made from partial combustion of charcoal. Diesel engines are somewhat fussier, but they can be "co-fueled" with some amount of liquid used to ignite a charge of air and a high-octane gaseous fuel. The addition of gaseous fuel to diesel intake air is called fumigation. Kits are available to fumigate propane into diesels to improve their power and reduce their smoke emissions.

Most current farm equipment has diesel engines. One of the features of the fast-crash doom scenario is that there will be little or no time to make major adaptations for different fuel supplies, so the most interesting possibilities are those which can be

- built from common materials and
- retrofitted to existing engines.

Are there significant possibilities out there? I believe there are. Here's a short list off the top of my head:

Straight vegetable oil (SVO). SVO is one step removed from biodiesel, but requires no methanol or other processing. It can be used directly after pressing so long as it is filtered so as not to clog pumps and injectors. SVO must be kept hot to thin it enough to atomize, so engines must be fully warm before using it. This can be accomplished by heating the fuel and coolant externally, or starting and warming up on petroleum diesel or biodiesel. The fuel system must be flushed of SVO before the engine is allowed to cool off again.

Supplies of SVO are likely to be limited, but if SVO is used for a "pilot injection" to ignite a charge of another fuel it can be stretched considerably.

Fumigated bio-gas. Bio-gas can be produced from animal wastes and stored in tanks. Introducing gas into diesel intake air creates a fuel-air charge which ignites and burns when oil is injected by the conventional fuel system. It is not usable as the sole fuel in a diesel engine, but it can stretch the supply of liquid fuel. A dual-fuel biomethane bus in the UK expects biomethane to supply 60-80% of its fuel. As no biomethane is used when the engine is at idle, agricultural equipment could expect to use a higher fraction of biogas than a bus.

The downside of biogas is that it is a gas, and storage cylinders are heavy and bulky. Materials likely to be on-hand would leave a a great deal to be desired: low-pressure cylinders such as propane tanks can contain biogas but would hold relatively little fuel even if it is purified to remove CO_2. A 250-gallon propane "pig" pressurized to 250 PSI would hold the equivalent of about 4 gallons of diesel fuel. It might be possible to get work done this way, but refueling would be very frequent and take a great deal of time away from work.

Fumigated producer gas. Gas does not have to be delivered to the vehicle; it can be produced on board from solid or liquid fuels. The technology for using gasogenes to produce fuel gas for a combustion engine was brought to a high level of refinement during previous periods of oil rationing (such as WWII). Gasogenes were revisited by the USDA during the 70's oil price shocks, and designs created which could be built out of available materials to power tractors in the event of fuel shortages.

Gasogenes can use most any dry combustible matter as fuel. Wood chips and charcoal are conventional feedstocks. Dried grass pellets and torrefied biomass are other possibilities. Combustible liquids may be used also; a liquid fuel which is not suitable for an engine's fuel system may be turned into a gas for fumigation.

5 Biofuel energy requirements

For the sake of argument, let's start with a sub-optimal energy system. Dried biomass loses very little of the original energy (though biomass may not remain dry unless it is stored correctly). Torrefaction retains roughly 90% of the energy of the original biomass in the product. Pyrolysis oil retains about 70%. Production of charcoal may yield about 50% in the solid product (the remainder comes off as gas and heat). Therefore, let's assume the use of charcoal as the fuel product.

Next, let's assume conversion of charcoal to producer gas in a gasogene. The fuel portion of charcoal is almost entirely carbon. Carbon has a heat of combustion of 93960 cal/mol, while carbon monoxide has 68560 cal/mol; 73% of the energy of carbon is retained in the gas product of the gasogene, not including any CO_2 from the exhaust gas recycled to CO using excess heat. The hypothetical conversion efficiency from biomass through charcoal to fuel gas in the vehicle is thus 37% (not including any productive use of heat or off-gas created in the production of the charcoal).

If the vehicle is a farm tractor or combine which requires 1 gallon-equivalent of energy per acre per pass, of which 90% is coming from fuel gas produced from charcoal, 5 passes per season requires 1.7 million BTU of biomass. A further 10% of liquid fuel, or 700 kBTU/ac/year, is needed for pilot ignition; since this is relatively small I'll just count it at volume parity with petroleum diesel. This comes to 0.5 gallon per acre per year.

6 Biofuel feedstock availability

The amount of available feedstock depends on the productivity of the crop and the fraction which winds up as byproducts, but we can get some estimates. At a yield of 150 bushels per acre, corn (maize) produces roughly 1.5 dry tons of excess stover (not needed for erosion control) per acre, of which [15-20%](#) (0.22-0.3 tons) is cobs. At 17.4 million BTU per ton, the actual fuel requirement is less than 0.1 tons of biomass. Corn would in fact yield a very large excess of biomass energy beyond the needs for farm machinery working the field.

Oil for ignition can also come from corn. At 0.5 gal/ac/yr, the ignition requirements can be met by the oil from about 2.5 bushels/acre of corn (0.2 gal/bu). The byproduct of pressing is also usable as food.

Other crops also appear to produce sufficient byproduct biomass. The yield of wheat straw from winter wheat is over 2 tons per acre.

If the main crop does not yield oil, some small amount of land can be devoted to oilseeds. Sunflowers or canola will do for this. At a yield of 77 gallons per acre, one acre of canola would supply ignition fuel to till and harvest 150 acres. Such a modest amount of oil would be easy to produce locally.

These figures suggest that the energy situation of most farms is not nearly as bad as some paint it. Even assuming the least-efficient pathway for converting biomass to vehicle fuel (charcoal), farms still appear to generate much more energy as non-food biomass than they need to run machinery. Machinery has the virtues of not having to be bred up from small initial stocks, requires no animal training and no major changes in farm practices and skills, and certainly is not going to be stolen and eaten.

6 Biofuel energy excess and nitrogen fixation

The amount of excess energy from crop byproducts suggests that they might be exchanged for other necessary farm inputs. For instance, bio-oil (pyrolysis oil) can be produced from almost any finely-divided dry biomass. It preserves about 70% of the energy of the biomass, and is a relatively dense liquid which seems fairly easy to handle. One ton per acre of corn stover would yield about 12.2 million BTU of bio-oil. If this were used as a natural gas substitute in an ammonia plant, it would suffice to produce roughly 680 pounds of ammonia, containing 560 pounds of nitrogen. Most nitrogen application rates for corn are under 200 pounds per acre (some recommendations as little as ~50 lb/ac), so corn would be enough to provide a large excess of nitrogen fertilizer also.

This analysis does not look at the energy economy of livestock operations. Anaerobic digestion of manure from cattle, chickens and swine produces more fuel gas than many of them can use; already many farms have turned into net producers of electricity generated from biogas. While the excess is small on the scale of society, it does suggest that rural farming areas may be able to keep the lights on without purchasing energy.

Conclusions

Some have suggested that shortages of petroleum could produce a collapse of mechanized farming in the near term, with all that implies. This scenario does not appear to be realistic. Known methods appear to be able to keep farm machinery operational using only the energy produced on farms themselves, mostly using food byproducts rather than dedicated fuel crops; this is considerably better than the food requirements of draft animals. The superiority of machinery over animal power, both for productivity and economy and reliability of energy supply, guarantees that it would continue to be maintained and used for some time even if the "fast crash" scenarios come to pass.

Endnotes

1 Assuming 1150 m^3 of natural gas per metric ton ammonia and 37 MJ/m^3 natural gas, ammonia requires approximately 43 GJ/tonne, or about 23 MJ per pound of nitrogen.