Evaluation of Biomass, Biofuels, and Biogas as Proposed Solutions to Air Pollution, Global Warming, and Energy Insecurity

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Bioenergy fuels are solid (biomass), liquid (biofuels), or gaseous (biogas) fuels derived from organic matter. Most bioenergy is derived from dead plants, animal excrement, or microbial degradation of either. **Biomass**, such as wood, grass, agricultural waste, and dung, is burned directly for home heating and cooking in developing countries and for electric power generation in most countries. **Biofuels** are generally used for transportation as a substitute for gasoline, diesel, jet fuel, or bunker fuel. **Biogas**, such as methane from a landfill, digester, or wastewater treatment plant, is used for either electricity, heat, or transportation.

Biofuels are discussed in Section 8.9. Biomass and biogas combustion are not recommended in a 100 percent WWS world for several reasons, discussed herein. Similarly, **biomass with carbon capture and storage** (**BECCS**) also represents an opportunity cost versus WWS, so is not recommended. One potentially acceptable application of biogas is methane pyrolysis, if the heat comes from a WWS source. These topics are discussed next.

8.8.1. Biomass and Biogas Combustion Without Carbon Capture

The main sources of solid biomass burned to produce electricity or heat are as follows[209]:

agriculture residues, which include dry crop residue (such as straw and sugar beet leaves), and livestock waste (such as solid or liquid manure);

forestry residues, which include bark, wood blocks, wood chips from treetops and branches, and logs from forest thinning;

energy crops, which include dry wood crops (such as willow, poplar, eucalyptus, and short-rotation coppice), dry herbaceous crops (such as miscanthus, switchgrass, reed, canary grass, cynara, cardu, and Indian shrub), oil energy crops (such as sugar beet, cane beet, sweet sorghum, Jerusalem artichoke, sugar millet), starch energy crops (such as wheat, potato, maize, barley, triticae, corn, and amaranth), and other energy crops (such as flax, hemp, tobacco stems, aquatic plants, cotton stalks, and kenaf);

industry residues, which include wood industry residues (such as bark, sawdust, wood chips, and cutoffs from saw mills), food industry residues (such as beet root tails, used cooking oils, tallow, yellow grease, and slaughterhouse waste), and industrial products (such as pellets from sawdust and wood shavings, bio-oil, ethanol, and biodiesel);

park and garden wastes, which include grass and pruned wood; and

contaminated wastes, which include demolition wood, municipal waste, sewage sludge, sewage gas, and landfill gas.

The primary reason biomass combustion is not recommended for use in a WWS world is that biomass combustion, like coal and fossil gas combustion, produces air pollution. A 100 percent WWS energy infrastructure is designed to eliminate air pollution. The problem is greatest with the burning of municipal waste, which usually contains toxic chemicals. In sum, whereas biomass is partly renewable, it is not clean. A 100 percent WWS world requires both clean and renewable energy rather than just renewable energy.

The second reason for not including biomass for electricity production is that it causes more global warming per unit of electricity produced than does WWS when all emissions are accounted for. Biomass grows by photosynthesis – it converts carbon dioxide and water vapor from the air into organic material and oxygen Although growing biomass takes carbon dioxide out of the air to grow, that carbon dioxide is returned to the air when the biomass is burned, and any residue is decomposed by bacteria. Biomass causes additional emissions of carbon dioxide during fertilizing, watering, growing, collecting, transporting, separating, and/or incinerating the biomass. These processes all require fossil-fuel energy and emissions.

The overall emissions from biomass used for electricity production ranges from 86 to 1,788 grams of CO_2-equivalent per kilowatt-hour of electricity, or 10 to 373 times the emissions per unit of electricity as onshore wind (Figure 8.1). These emissions are due largely to lifecycle emissions (43 to 1,730 grams of CO_2-equivalent per kilowatt-hour of electricity). A review[209] suggests that the combustion of forestry and industry residues may result in the least emissions (43 to 46 grams) among biomass fuels. Combustion of agricultural residues and energy crops may cause higher emissions (200 to 300 grams). Combustion of municipal solid waste may cause the most emissions (mean of 1,730 grams). The low emissions from forestry and industry residues are due to the fact that the feedstock in those cases does not need to be produced actively as it does with agricultural residues or energy crops. The high emissions from burning municipal solid waste are due to emissions from the energy required to collect, segregate, sort, transport, and incinerate the waste.

Biomass energy facilities have opportunity-cost emissions of 36 to 51 grams of CO_2-equivalent per kilowatt-hour of electricity generated because they take 4 to 9 years between planning and operation versus two to 5 years for onshore wind or utility PV. During the additional time, the background grid is emitting.

Other sources of climate-affecting emissions due to using biomass for electricity are heat and water-vapor emissions during biomass combustion. Because biomass combustion is less efficient than is coal combustion, biomass combustion releases more heat per unit of electricity than does coal combustion.

A third problem with some types of biomass, particularly energy crops, is that they require much more land than WWS does. Given that photosynthesis is only one percent efficient at converting sunlight to biomass energy, whereas solar PV panels are now 20 to 47 percent efficient at converting sunlight to electricity, a solar panel needs less than one-twentieth the land to produce the same energy as a biomass crop.

Biogas from a landfill, digester, or wastewater treatment plant contains 45 to 75 percent methane by volume. The rest is mostly carbon dioxide. Burning biogas for electricity, heat, or transportation faces the same issues as burning biomass. An alternative to burning biogas is to use its methane to produce hydrogen by methane pyrolysis (Section 7.2). This process minimizes methane emissions and emits no carbon dioxide so long as the heat required for it comes from a WWS source. The hydrogen can be used to generate electricity in a fuel-cell vehicle (displacing the need for gasoline); in a fuel cell for electricity generation (displacing the need for fossil gas to do the same thing); or for steel or ammonia manufacturing (displacing the need for coal or fossil gas, respectively, for those processes).

In sum, burning forest and industry residue and other forms of biomass to provide electricity and heat, or burning biogas to provide electricity, heat, or transportation, results in higher CO_2-equivalent emissions and more air pollution than does using WWS. Some forms of biomass also require much more land than WWS does. As such, using biomass or biogas for energy represents an opportunity cost. The exception is to use biogas to produce hydrogen by methane pyrolysis, where the hydrogen is subsequently used in a fuel cell or for steel or ammonia manufacturing.

8.8.2. Biomass and Biogas Combustion with Carbon Capture

A proposed method of reducing biomass and biogas CO_2-equivalent emissions, and even creating negative carbon emissions, is to combine biomass and biogas combustion with carbon capture and storage to give **biomass (or biogas) with carbon capture and storage or use** (**BECCS/U**). Negative carbon emissions arise if a process removes more carbon from the air than it adds to the air.

BECCS would theoretically result in negative carbon emissions if, for example, forest wood residue (containing carbon dioxide from the air) were collected; little energy were used to collect, transport, and incinerate the wood; and the carbon dioxide were captured from the exhaust stream of the biomass electricity-generating facility and pumped underground. If successful, this method would be a one-way conduit for carbon dioxide to go from the air to underground, thereby resulting in negative carbon emissions.

The problems, however, are several-fold. As with fossil gas and coal with carbon capture, the carbon capture system with BECCS/U requires 13 to 44 percent more energy than without it[200]. If that energy comes from fossil gas, coal, or biomass, 13 to 44 percent more air pollution occurs with BECCS/U than without capture. Biomass and biogas combustion without carbon capture already produce substantial air pollution, whereas WWS produces none.

Similarly, as with carbon capture for coal and fossil gas, the carbon dioxide reductions with BECCS/U are 10 to 80 percent[198], much lower than anticipated due to the high energy requirements of carbon-capture equipment. Leakage of carbon dioxide from underground storage or from industrial use is also an issue.

Second, as with fossil gas and coal, few reliable underground storage facilities exist for BECCS. Because of the high cost of carbon capture, biomass with carbon capture facilities are likely to couple with for-profit uses of the carbon dioxide, such as enhanced oil recovery or electro-fuel production, both of which require energy and produce combustion fuels, resulting in additional carbon dioxide and air-pollution emissions.

Third, the efficiency of biomass combustion for electricity (electricity output per unit of energy in the fuel) is low (20 to 27 percent), even compared with the efficiency of coal combustion (33 to 40 percent). Thus, a large mass of biomass is needed to produce a small amount of electricity. As such, if BECCS/U were to provide negative emissions on a large scale, substantial land areas dedicated to biomass crops would be needed to maintain a continuous energy supply. Consequently, a share of agricultural land would be used for fuel instead of food, increasing the price of food. Higher food prices trigger deforestation by incentivizing people to turn high-carbon-storage forestland into low-carbon-storage agricultural land.

Fourth, removing agricultural residues usually means crops need to be fertilized more since the residues contain nutrients that are no longer available once they are removed. Fertilizers contain nitrous oxide, a greenhouse gas, and ammonia, a major air pollutant. Both are emitted to the air. Finally, the cost of BECCS/U is high, even compared with CCS for fossil fuels. In fact, as of 2023 no BECCS/U facility existed in the world for capturing carbon dioxide emissions from a biomass-to-electricity-and-heat power plant[195].

In sum, paying for BECCS/U instead of WWS means less energy production, a longer time lag between planning and operation, more air pollution, greater land use (for some crops), and less carbon removal. As such, BECCS/U is not recommended.

8.9. Why Not Liquid Biofuels For Transportation?

Liquid biofuels are used primarily for transportation as a substitute for gasoline or diesel. The most common transportation biofuels are ethanol, used in passenger cars and other light-duty vehicles, and biodiesel, used in many heavy-duty vehicles. Ethanol is also being proposed for use in aviation fuel. Liquid biofuels should not be part of a 100 percent WWS transition since they result in substantial air-pollution deaths and illnesses, climate damage, land consumption, and water use relative to WWS. This conclusion applies whether or not equipment is added to ethanol refineries to capture carbon dioxide from them. This section discusses these issues.

Ethanol is produced in a refinery, generally from corn, sugarcane, wheat, sugar beet, or molasses. The most common among these sources are corn and sugarcane, resulting in the production of **corn ethanol** and **sugarcane ethanol**, respectively. Microorganisms and enzymes ferment sugars or starches in these crops to produce ethanol in an **ethanol refinery**.

Fermentation of cellulose in switchgrass, wood waste, wheat, stalks, corn stalks, or *Miscanthus*, also produces ethanol, called **cellulosic ethanol**. However, the process of producing cellulosic ethanol is more energy intensive than is fermentation of sugar and starches because the breakdown of cellulose by natural enzymes (as it occurs in the digestive tracts of cattle) is slow. Faster breakdown of cellulose requires genetic engineering of enzymes.

Ethanol as a transportation fuel may be used on its own, as is done frequently in Brazil, or blended with gasoline. Common blends of ethanol are **E10, E15, and E85**. E10 contains 10 to 10.49 percent ethanol mixed with gasoline; E15 contains 10.5 to 15 percent ethanol mixed with gasoline, and E85 contains 51 to 83 percent ethanol mixed with gasoline[210]. Pure ethanol (E100) in Brazil contains no gasoline. However, in the United States, E100 must contain at least 2 percent gasoline as a **denaturant**, which is a poisonous or foul-tasting chemical added to a fuel to deter people from drinking it. Thus, if 15 percent gasoline is blended with 85 percent E100, the resulting mixture (E85) contains 83.3 percent ethanol and 16.7 percent gasoline, which is why the upper limit of the ethanol content in E85 is 83 percent.

Gasoline vehicles can use either pure gasoline (E0) or E10 fuel, but higher ethanol blends can damage the vehicles. Instead, higher blends (E15 and E85) must be used in a flex-fuel vehicle (FFV), which can also run on E0 or E10. By far, most ethanol today in the United States is blended as E10. However, due to the planned phase-out of gasoline based on climate concerns, the increased development of FFVs, and tax subsidies promoting ethanol, the use of E85 is increasing rapidly. In Brazil, the use of E100 is already widespread.

A proposed alternative to ethanol for transportation fuel is **butanol**. It can be produced by fermenting the same crops used to produce ethanol but with a different bacterium, *Clostridium acetobutylicum*. Butanol contains more energy per unit volume of fuel than does ethanol. However, unburned butanol also reacts more quickly in the atmosphere than does unburned ethanol, speeding up ozone production relative to ethanol. Ozone is harmful to those who breathe it. On average, ethanol for transportation produces more ozone than does gasoline for transportation in most regions of the United States[211,212,213].

Biodiesel is a liquid diesel-like fuel derived from vegetable oil or animal fat. Major edible vegetable oil sources of biodiesel include soybean, rapeseed, mustard, false flax, sunflower, palm, peanut, coconut, castor, corn, cottonseed, and hemp oils. Inedible vegetable oil sources include jatropha, algae, and jojoba oils. Animal-fat sources include lard, tallow, yellow grease, fish oil, and chicken fat. Soybean oil accounts for about 90 percent of biodiesel production in the United States. Biodiesel derived from soybean oil is referred to as **soy biodiesel**.

Biodiesel is produced by the chemical reaction of a vegetable oil or animal fat (both lipids) with an alcohol. It is a standardized fuel designed to replace diesel in standard diesel engines. It can be used as pure biodiesel or blended with regular diesel. Blends range from 2 percent biodiesel and 98 percent diesel (**B2**) to 100 percent biodiesel (**B100**). Generally, only blends B20 and lower can be used in a diesel engine without engine modification. The use of vegetable oil or animal fat directly (without conversion to biodiesel) in diesel engines is also possible; however, it results in more incomplete combustion, thus more air-pollution byproducts, as well as a greater buildup of carbon residue in, and damage to, the engine, than does biodiesel.

Significant efforts have been made to produce **algae biodiesel**, which is biodiesel from algae grown from waste material, such as sewage. However, these efforts have been hampered by the fact that algae can grow quickly only when exposed to the sun. As such, algae cannot grow quickly when one layer is piled on top of the other. Instead, algae must be spread, in a single layer, over a large unshaded area. Each volume of oil produced from algae also requires about 100 times that volume of water. Both factors have limited the growth of the algae biodiesel industry.

Liquid biofuels (corn ethanol, cellulosic ethanol, butanol, and biodiesel) are not recommended as part of a 100 percent WWS energy infrastructure. This conclusion applies whether or not carbon dioxide capture equipment is added to refineries producing the biofuel. The reasons liquid biofuels are not recommended are (1) nearly all biofuels are burned, resulting in air pollution similar to that from fossil fuels; (2) with or without carbon capture, liquid biofuels do not reduce CO_2-equivalent emissions nearly to the extent that WWS-powered battery-electric or hydrogen fuel-cell vehicles do; (3) without carbon capture some liquid biofuels increase CO_2-equivalent emissions relative to fossil fuels; (4) with or without carbon capture many biofuels require rapacious amounts of land; (5) many biofuels require excessive quantities of water; and (6) many biofuels are derived from food sources, increasing food shortages, food prices, and starvation[178,214,215]. Because liquid biofuels cause greater climate, pollution, land, water, and food problems than WWS technologies, biofuels, with or without carbon capture, represent opportunity costs, as discussed next.

8.9.1 Corn-Ethanol Refined Without Carbon Capture

The main issues with liquid biofuels, even without considering carbon capture, are illustrated by comparing the impacts of using corn ethanol to power internal-combustion-engine vehicles with the impacts of using wind or solar to power battery-electric vehicles.

First, replacing gasoline vehicles with battery-electric vehicles powered by wind reduces energy requirements and carbon emissions substantially. It reduces energy requirements by about 75 percent due to the efficiency of electricity over combustion and reduces CO_2-equivalent emissions from gasoline production and combustion by 99.3 to 99.8 percent[178]. The remaining emissions are due to the fossil energy required to build and decommission the wind turbines. In comparison, using corn- or cellulosic-E85 vehicles increases or hardly changes energy needs or CO_2-equivalent emissions relative to using gasoline vehicles. This is quantified as follows.

First, proponents of corn ethanol argue corn-ethanol vehicles should reduce CO_2-equivalent emissions versus gasoline vehicles for 3 reasons: (1) carbon dioxide removed from the air by photosynthesis during corn growth offsets carbon dioxide emitted from fermentation and combustion during ethanol production and vehicle use, respectively; (2) carbon dioxide emitted during ethanol production is modest; and (3) land-use change emissions associated with corn production are small.

However, corn-ethanol production requires a lot of fossil-fuel energy, thus CO_2-equivalent emissions, to grow, fertilize, water, and cultivate the crop; transport the crop; refine the crop into fuel; and transport the fuel to market. Fertilizer use during corn production also emits nitrous oxide. Ethanol is too corrosive to be used in pipes, so ethanol must be transported by train, truck, or barge, all of which emit diesel exhaust, which contains black and brown carbon particles, the second-leading cause of global warming. Finally, using corn for fuel instead of food drives up corn prices, increasing deforestation, including of rain forests, to produce agricultural land, the least carbon-intensive use of land, further driving up emissions.

The US renewable fuels standard (RFS) is a policy that motivated the use of ethanol fuel in the US, from 2008 to 2016. A detailed study[216] of the RFS concluded that it increased corn prices by 30 percent, expanded US corn cultivation by 8.7 percent, increased fertilizer usage by 3 to 8 percent, increased water quality degradants by 3 to 5 percent, and caused enough domestic land-use-change emissions such that "the carbon intensity of corn ethanol produced under the RFS is no less than gasoline and likely at least 24 percent higher." In comparison, using wind to power battery-electric vehicles reduces gasoline-vehicle CO_2-equivalent emissions by 99.3 to 99.8 percent[178].

The air-pollution mortality associated with both corn- and cellulosic-ethanol vehicles also significantly exceeds that associated with WWS-powered battery-electric vehicles[178,211]. The reason is that battery-electric vehicles have no tailpipe emissions. Thus, their only emissions are from the upstream production of wind turbines, solar panels, and the vehicles themselves; tire wear; and some brake-pad wear. Because electric vehicles use regenerative breaking, their brake pads are hardly engaged, so brake-pad emissions are very low.

On the other hand, E85 vehicles have high air-pollution emissions from their tailpipes, producing and transporting the ethanol, tire wear, brake-pad wear, and manufacturing the vehicle. E85's tailpipe emissions cause health impacts that often exceed those of gasoline vehicles[178,213,217,218,219], especially at low temperatures[212,220]

Another problem with using ethanol as a fuel is water consumption. The average US irrigation rate of corn is 13.2 percent[178]. Irrigating the corn crop needed to power an entire US on-road flex-fuel-vehicle fleet powered by E85 would require about 10 percent of the entire US water supply[178].

Finally, because of the substantial land required for corn or cellulosic ethanol, neither can provide enough energy for more than a few percent of a US vehicle fleet. In fact, the land required to grow corn for an E85 flex-fuel vehicle fleet is 80 to 100 times that needed for solar PV to power a battery-electric vehicle fleet. The reason is as follows. Photosynthesis is only one percent efficient. Most PV cells, on the other hand, are 20 to 26 percent efficient. Thus, a PV farm needs only one-twentieth to one-twenty-sixth of the land to produce the same energy as a corn crop needs. Further, BEVs convert 80 percent of the electricity from a plug to battery electricity and then motion. The rest is waste heat. FFVs running on E85 convert only about 20 percent of energy in the E85 to motion. So, driving a BEV requires 1/4th the energy as driving a FFV. Combining the PV-to-photosynthesis efficiency with the BEV-to-FFV efficiency suggests that driving a BEV powered by PV requires 1/80th to 1/100th the land as driving a FFV powered by E85 from corn ethanol[178].

A wind turbine requires less than one-five-thousandth of the footprint on the ground (accounting for only the pole in the ground plus a cement base) as does a PV farm to provide the same electricity. As such, wind-powered BEVs may need less than one-four-hundred-thousandth the land footprint as FFVs powered by corn-E85[178]. Wind turbines do require space between them to prevent interference of the wakes of one turbine with another. However, even the spacing area for wind turbines powering BEVs may be one-tenth to one-twentieth of the land needed to grow corn for

E85 powering FFVs[178]. Because most wind spacing area is open space between turbines, crops can still grow and PV panels can operate between wind turbines.

In sum, liquid biofuels are not recommended in a 100 percent WWS world because of their high climate, health, water-supply, and land issues. This conclusion applies even when carbon capture is considered, as discussed next.

8.9.2 Corn-Ethanol Refined with Carbon Capture

Many argue capturing carbon dioxide from ethanol refineries, then piping it to an underground sequestration site, should reduce CO_2-equivalent emissions relative to corn-ethanol without carbon capture for running flex-fuel vehicles. To the contrary, corn-ethanol with carbon-capture equipment and carbon-dioxide pipelines appear to be an opportunity cost that may damage climate and air quality, occupy land, and saddle consumers with high fuel costs for decades[68].

In theory, capturing carbon dioxide during the fermentation process of ethanol production may reduce ethanol-FFV lifecycle CO_2-equivalent emissions to slightly below those of gasoline[221]. However, not only are the resulting emissions still high, but the comparison with gasoline alone ignores the fact that BEVs emit far less than both FFV and gasoline vehicles and ignores the impacts of ethanol-fueled FFVs on air pollution, land use, and water supply[178,211].

Transition highlight. To bolster the argument for using ethanol-fueled FFVs as a climate solution, several companies proposed capturing carbon dioxide during ethanol-refinery fermentation, then building over 3,000 kilometers of pipes under hundreds of landowners' properties across 5 US states (Iowa, South Dakota, North Dakota, Nebraska, and Minnesota) to transfer and store the carbon dioxide underground[222]. What is the opportunity cost of such an "ethanol plan" (capturing fermentation carbon dioxide from ethanol refineries, building a pipeline, storing the carbon dioxide underground, blending the ethanol to produce E85, then using the E85 in FFVs) versus investing the same funds to build wind turbines to run battery-electric vehicles ("wind plan")? The wind plan eliminates the need to produce ethanol for vehicles, emit vehicle exhaust, emit pollution from ethanol refineries, or sequester carbon dioxide from ethanol refineries.

Results suggest that if the same investment allocated for the ethanol plan ($5.6 billion) were spent instead on the wind plan, drivers in the 5 states would save $66.9 to $111 billion over 30 years in fuel costs alone due to the price difference between E85 and residential electricity and the far better mileage per unit of energy of a battery-electric Ford *F-150* truck (the example used in the study) versus a Ford *F-150* FFV. Even with an upfront BEV cost $21,700 higher than the FFV cost, the savings from the wind plan are still $39.5 to $65.6 billion over 30 years[68].

Further the wind plan may avoid 2.4 to 4 times the CO_2-equivalent emissions as the ethanol plan. This accounts for emissions associated with building wind farms, batteries for BEVs, carbon-dioxide pipelines, ethanol refineries, and carbon capture systems; and for growing, cultivating, and transporting corn. Finally, the wind plan may significantly reduce air pollution and land needs compared with the ethanol plan.

In sum, investing in wind turbines to provide electricity for BEVs is far better in terms of cost, carbon emissions, land use, and air pollution than making the same investment in capturing carbon dioxide from ethanol refineries, piping the carbon dioxide to an underground storage facility, and using the ethanol to produce E85 for FFVs[68].

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