

Chapter 2

Combustion

Abstract Combustion is the process that separates carbon atoms from fuel in the presence of oxygen. It is an exothermic reaction; energy is released as heat and light. The by-products of complete combustion of a pure fuel containing only atoms of carbon and hydrogen are carbon dioxide (CO_2) and water (H_2O). Biofuels are considered renewable fuels because they are made from carbon-containing substances that can be replenished annually. Biofuels are made from plant oils and sugars, the most common being ethanol and biodiesel. Fossil fuels are combustible substances created by geologic forces over time. Solid wastes containing carbon can also be burned.

Keywords Carnot cycle · Biodiesel · Kyoto protocol · Paper pellets · Co-generation · Ethanol

Combustion is the process that separates carbon atoms from fuel in the presence of oxygen. It is an exothermic reaction; energy is released as heat and light. The by-products of complete combustion of a pure fuel containing only atoms of carbon and hydrogen are carbon dioxide (CO_2) and water (H_2O) (Glassman et al. 2014; Baukal 2012; Green and Perry 2007). This chapter contains descriptions of combustible fuels, such as biofuels, fossil fuels and solid waste.

2.1 Biofuels

The Energy Independence and Security Act of 2007 provided millions of dollars to develop alternative fuels (USG 2007). Biofuels are considered renewable fuels because they are made from carbon-containing substances that can be replenished annually. Ethanol and biodiesel are liquid biofuels. Biomass means plant or animal material (Schobert 2013). Biomass burning refers to the deliberate use of combustion to reduce the volume of biological solid waste. For example, in Brazil, the plant material left over after harvesting sugar cane is incinerated to generate electricity. Biomass contains elements other than carbon and hydrogen; therefore, biomass

burning releases compounds other than water and carbon dioxide. Released carbon particulates are commonly called soot.

According to carbon commodities traders, plants grown and burned within 12 months are not counted in a country's carbon budget. This accounting trick encourages biomass burning to generate electricity regardless of the accompanying release of carbon particulates and other chemical compounds. Some incinerator facilities efficiently and completely combust biomass, emit water and carbon dioxide, and control the release of other compounds, including ash. Some incinerator ash contains hazardous compounds.

In countries lacking modern farm machinery, stubble left in the field after harvest is burned rather than tilled. Open burning is an incomplete combustion process that releases various gases and unburned carbon-containing soot particles. Think of forest fires. Soot is a pulmonary irritant which contributes to the incidence of asthma. Some types of soot are carcinogenic. Once in the atmosphere, they serve as cloud concentration nuclei (Chavez et al. 2013; Scholtens et al. 2014). In the upper atmosphere, carbon-based particulates may contribute to global cooling by absorption of solar radiation.

2.1.1 Biodiesel

Biodiesel is made from animal fats or vegetable oils through a process called transesterification. The fatty acids react with either ethanol or methanol. There are five common method of production. Byproducts include soap and glycerol with some excess alcohol, and trace amounts of water. Early reports of biodiesel production focused on individuals who collected waste fats from local restaurants and converted them.

2.1.2 Ethanol

Biofuels are made from plant oils and sugars, the most common being ethanol and biodiesel. To reduce transportation-related emissions of CO₂ in the United States, the USEPA mandated that ethanol be blended with gasoline. At the time, it seemed like a win-win situation. Global Warming activists cheered. Pacifists supported the ethanol mandate because it supposedly reduced the amount of oil imported from the Middle East. Planters celebrated because it created demand for corn. Academia rejoiced at the availability of federal dollars for renewable fuels research.

The chemical properties of ethanol are of concern. Ethanol cannot be shipped by pipeline because it is corrosive; it is trucked. Automobile engines may be damaged when the concentration of ethanol exceeds 10% per gallon of gasoline. The mileage per gallon of blended fuel is less because the energy potential of ethanol is lower than gasoline. The BTU equivalent cost to make, transport, and blend one gallon of ethanol is 0.9 gallons of gas. However, 10% of a million is 100,000. Blending

ethanol with gasoline replaces a daily average of 36,851,000 gallons of gas, approximately 877,000 barrels of oil (USDoe 2013).

In the United States, ethanol is made primarily from corn, because of its high sugar content, although other plant material such as switchgrass, sugar cane, and algae can be used (USEPA 2014a). Much of the corn in the Great Plains region, especially Iowa, is now grown for the ethanol market. Corn is also sold as livestock feed. As the price of corn increases, the price of milk and meat increases at the grocery store. Corn farmers point out that the brewers grains left over after the production of ethanol are sold as livestock feed. Nothing is wasted.

Ethanol production, whether for liquor or fuel, is water-intensive. It requires between 3 and 5 gallons of water for each gallon of ethanol produced. <http://web.extension.illinois.edu/ethanol/wateruse.cfm>. This creates an ethical dilemma for farmers in the Great Plains region and parts of Texas which depend on irrigation water from an underground aquifer which is not replenished when it rains. Naturally, ethanol plants are sited on several large rivers that cross the Great Plains. The Missouri River originates in Montana, crosses North and South Dakota, and forms the western border between Nebraska and Iowa and a portion of the border between Kansas and Missouri before it crosses Missouri to meet the Mississippi at St. Louis. The Mississippi River originates in Minnesota and forms the eastern borders of Iowa, Missouri, and Arkansas and bisects Louisiana. Water removed from the river is not returned as treated effluent, rather some evaporates and some remains in the distillers grains, which may be sold for livestock feed. Some downstream communities complain about the reduced volume available for their use.

The ethanol boom has made it financially attractive to cultivate parcels with marginal soils or challenging topography. Farmers who were barely scraping by have been able to replace broken equipment and pay off mortgages. Agribusinesses have made millions from producing corn for ethanol. These people support the EPA mandate.

Political Action Committees (PACs) are attempting to sway the debate. Conservationists in Prairie States have been dismayed to discover that abandoned agricultural land previously enrolled in the Conservation Reserve Program to preserve the native grasses of the prairie have been planted in corn (USEPA 2010). Bottom land that attracted migratory water fowl, because it was too wet to plow, has been filled and tilled. Organizations such as Ducks Unlimited and the Audubon Society have stepped up their fundraising efforts to preserve wetlands. Others want to reintroduce the buffalo to the plains. Land ownership is the key for conservation and many conservationists prefer public ownership of selected sites. Government entities meanwhile are assailed by increasing demands for services that have been financed by lease payments for growing, grazing or mineral rights. Which public good trumps all others?

The media has given much attention to the food for fuel issue. Has the ethanol mandate actually increased food prices? Looking at Table 2.1, the value of a bushel of corn in Oct 2013 is higher than it was in Oct 2009, but lower than a year ago. The price for other grains has also fluctuated. Is this a function of land use, crop yields, weather, or public policy? Prices are given in metric tonnes (metric

Table 2.1 Comparison of Grain Prices*

	2009	2010	2011	2012	2013
Rice	566.25	533.13	602.14	584.74	453.26
Soybeans	354.86	427.18	446.02	565.53	472.83
Wheat:	198.85	270.23	289.01	358.20	325.69
Sorghum	159.05	201.04	263.67	283.07	205.25
Corn	167.22	235.70	274.78	321.63	201.75
Barley	130.55	174.61	208.68	250.04	159.28

*price given in US dollars/metric ton as of Oct

ton=1000 kg=2025 lbs.), which is slightly larger than an English ton at 2000 lbs. The number of bushels per metric tonne depends on the size and weight of the harvested grain. The price reflects the weather more than any other factor (Index Mundi 2014).

2.1.3 Wood

Wood is a biofuel. It is considered a renewable resource; however, trees are harvested in 5-10-20 year cycles rather than annually. To account for the carbon emitted when burned, the amount of carbon sequestered during the current/last year can be subtracted from the total carbon content of the tree products burned. The benefits of trees include fuel, shade, oxygen formation, soil enhancement through root growth, some reduction of ambient particulate concentrations and wind erosion, absorption of storm water, and artistic appeal. Naturally, trees have other uses: building elements, paper, fabrics, cellulose, food, various chemical compounds, mulch, etc. The Biofuels Center of North Carolina advocates harvesting wood debris for fuel rather than using a prescribed burn, which may kill off endangered wildlife (Wall 2011)

The growth rate of trees/plants is positively correlated with the ambient concentration of CO₂. Tree rings provide an indication of the amount of biomass added and carbon sequestered each year. A comparison of growth rings shows that on average urban trees grow slower than rural trees, experience more stress, and are likely to die sooner.

Trees in an urban environment may negatively impact infrastructure. Roots cause upheaval/cracks of sidewalks and pavements and penetrate water, sewer, and septic lines. Falling branches/trees may damage power lines or property. Thus, an urban forestry management program requires regular inspection, pruning and replacement of tree stock. Many municipalities establish separate landfills for plant material.

In some areas, trees may enhance landscaping and may improve property values. For example, a healthy 50-year old oak located in the front yard of a suburban residence may be highly valued, but the same tree planted next to a structure or a driveway may be a nuisance. Farmers often use stands of trees along the western property line to prevent soil erosion from wind.

There are some advantages of planting trees in the median of an interstate highway. A stand of trees may improve safety by preventing errant drivers from accidentally driving into oncoming traffic, or by blocking the glare of headlights. The trees provide habitat for birds and other animals. Pollen, seeds, and insects are often carried on the wind; trees slow the wind and therefore, may slow the advancement of some non-native species. During a severe weather event, portions of the road may become blocked by downed trees. It is extremely rare for communities to either harvest fallen timbers or hay from the median strips. Perhaps that will change.

The most common ethical challenge when promoting biofuels is to present the complete picture. The cost of alternative fuels exceeds the cost of petroleum-based fuels in almost every instance. Different procedures are required to handle and store alternative fuels; they are not always onerous. The performance of these fuels in existing machines does not meet the same standards. Undoubtedly the technology will change. The primary benefit is that we are developing alternatives now rather than waiting until the supply of fossil fuels is threatened. Achieving energy independence is a noble goal for our domestic agenda.

2.2 Fossil Fuels

Over geologic time, plants and animals have lived and died. Natural forces have changed and shaped the crust of the earth. Continents have broken and drifted, creating mountain ranges and other land forms. The climate has changed from ice age to temperate in an unrelenting cycle (Lomborg 2001). Folding crust and massive ice sheets have created compressed carbon deposits which we now burn: coal, gas and oil.

2.2.1 Coal

Coal is thought to be the most abundant fossil fuel with reserves in the United States estimated sufficient for two hundred years or longer, a mere moment in geologic time. Communities of free men extract coal by hand in shafts dug deep into the earth. Their culture is full of stories and song about the miners and mine disasters, young widows and black lung disease. Strip mining near surface deposits seems in contrast to be safer and healthier. The anti-coal policies of the Obama Administration intentionally discourage demand in the United States for this abundant, cheap energy source; however, the Fukushima nuclear disaster in Japan has led to an increase in the demand for coal worldwide.

The discovery of coal as a fuel source is not recorded in any history book; however, the similarity between charred wood and coal is hard to miss. From camp fire to cook fire to hearth, coal burned hotter and longer than wood. Denser and lighter in weight, coal fueled the industrial revolution.

The chemical by products of coal combustion depend on the amount of available oxygen and the temperature of the fire. With insufficient air, deadly carbon monoxide (CO) and hydrogen gas (H_2) are produced. With excess air, carbon dioxide (CO_2) and water (H_2O). Other elements in coal include sulfur (S), and nitrogen (N) with traces of mercury (Hg^+), chlorine (Cl^-), arsenic (As), selenium (Se) and other elements (Glassman et al. 2014; Baukal 2012; Green and Perry 2007).

Under the CAA, areas that are not in attainment for the NAAQS must evaluate all proposed new sources or major modifications to existing sources to avoid further deterioration of the ambient air quality. In effect, the NAAQS limits the development of new coal-fired power generating facilities. Air pollution dispersion models such as AERMOD and CalPuff predict the impact of adding another emissions source to a specific location by estimating ambient concentrations of specific pollutants of interest. These models require access to geographic and land use data, chemical transport principles, and meteorological data.

Utilities are highly regulated to prevent price gouging. The cost of adding pollution control equipment such as scrubbers and electrostatic precipitators and carbon capture and storage (CCS) technology to proposed coal burning facilities is likely to exceed the expected profit margin of the operation. The utilities may then apply for a rate increase to make their stock attractive to shareholders. The 2013 version of USEPA proposed regulations limits every emission except water emissions from coal-fired power plants (USEPA 2013).

Once the President announced a war on coal, savvy investors sold coal stocks. Coal companies found it harder to access capital. Jobs in coal mining towns dried up. The ethical question is whether this energy policy was intended to move the country closer to energy independence or not. Was it part of a long term Green Energy strategy or simply market manipulation and political retribution?

2.2.2 *Natural Gas*

A molecule of natural gas contains carbon and hydrogen atoms. When completely burned in the presence of oxygen, carbon dioxide (CO_2) and water (H_2O) are produced. The most common natural gas is methane (CH_4), consisting of one carbon atom and four hydrogen atoms. CH_4 is formed during the decomposition or digestion of plant and animal materials. CH_4 is a highly reactive greenhouse gas, estimated to be 50 times more harmful in the stratosphere than CO_2 . Atmospheric collisions between CH_4 and the hydroxyl radical (OH) produce water vapor. Natural gas is odorless and colorless. For safety, an odorous chemical compound hydrogen sulfide (H_2S) is added to natural gas carried through distribution systems. Domestic uses include home heating systems, gas stoves for cooking, gas fireplace inserts, and gas water heaters. CH_4 is also used as a transportation fuel. Since it contains fewer carbon atoms than gasoline, cars using a blend of ethanol and gasoline get fewer miles per gallon than cars burning regular gasoline. Removing H_2O from landfill gas is a technical problem generally solved by condensing out the H_2O . Ensuring that the CH_4 meets contract specifications is a basic ethical decision.

2.2.3 Petroleum

Petroleum is a fossil fuel formed by geologic events acting on plants, such as algae, and animals, such as zooplankton, trapped under ancient sedimentary rock deposits. The process of recovering the deposits is called “drilling for oil”. Petroleum products include liquids and gases containing carbon compounds. Within the geologic formation, petroleum can be dispersed in sand, trapped in shale, or pooled. Early recovery focused on liquid oil. Current methods such as fracking can extract oil and gas from sand and shale.

During the refining process, gases containing different numbers of carbon atoms are separated by their boiling point and captured. The name of the gas is related to the number of carbon atoms and/or its molecular structure. For instance, octane contains eight carbon atoms. The lighter compounds are used for transportation fuels. Heavier liquid compounds are used for lubrication of machinery. Paraffin has common household uses, for instance in candles or to seal jars of jam. The heaviest compounds are called bitumen, asphalt, pitch or tar and are used in road construction or as a sealant. The boiling point of these heavy compounds is above 500° F. During the combustion process, the carbon atoms are released from the fuel and react with oxygen atoms. This can be a multi-step process.

Petroleum-based fuels are ideal for transportation because they are safe and they have a high heat capacity per ton, measured in BTUs. This means that more fuel can be carried in a smaller space. The improvement in air quality in Pittsburgh, PA is partially attributed to the switch from coal-fired boilers to gas turbine engines on river barges and partially attributed to the economic ruin of the steel industry in the United States. Train safety was likewise improved when diesel-powered engines replaced coal and wood-fired boilers.

Petroleum-based fuels are used in aviation. Diesel fuel is adequate for some compression ignition engines, while others respond better to kerosene or jet fuel with a lower viscosity. Piston-engines use a high-octane gasoline. Environmental concerns with air travel include noise during take off and landing and when jets flying faster than MACH 1 break the sound barrier; the emission of air pollutants, in particular unburned hydrocarbons, NO_x and SO_x; and soil and water pollution from de-icing compounds, oil and fuel.

2.3 Solid Waste

Solid waste includes human excrement, food waste, industrial wastes, yard wastes, assorted garbage, combustion by-products, and all sorts of discarded objects, such as clothing, furniture, electronics and appliances, tires, and construction debris. Although some countries encourage residents to recycle their cast-off items and to compost their food and yard wastes, a large volume of waste remains. Incineration is a method used to burn solid wastes. It produces high temperatures. This heat may be used to generate steam.

Medical incinerators are used to burn human tissue, plastics, sponges, blood-contaminated substances, radioactive substances, and other biohazards. Emissions are regulated to limit the release of radioactive particles as well as the criteria pollutants. In 2014, the National Health Service (NHS) in Great Britain was roundly criticized for burning aborted fetuses and other human tissues in a waste-to energy incinerator without informing patients of other disposal options, including burial. <http://www.telegraph.co.uk/health/healthnews/10717566/Aborted-babies-incinerated-to-heat-UK-hospitals.html>

Solid waste incinerators are used to burn garbage. The first municipal solid waste incinerators created tons of ash containing hazardous metallic compounds. This problem was alleviated in part by removing steel, aluminum, batteries, and electronic waste from the garbage.

Some waste water treatment centers incinerate sludge. The City of Palo Alto CA sells their ash to a mining company which extracts silver and gold from Silicon Valley sludge (Bishop 1995). Each of these incinerators emits carbon dioxide and water vapor while reducing the volume of solid waste that is transported to landfills.

2.3.1 Tire-Derived Fuel

In the United States, approximately 290,000,000 tires are scrapped annually (USEPA 2014b). Discarded tires from motorized vehicles are a persistent environmental and health hazard. Discarded tires clutter the landscape and occupy valuable landfill space. Water accumulates inside tires and provides a breeding ground for mosquitoes. How can tires be eliminated as waste?

Although the carbon content of rubber made it a potential fuel, research into tire disposal and reuse identified two problems: the steel belt and sulfur. A machine was developed to remove the steel belt from the tire. The tire was then placed on a conveyor to a second machine which chopped it into small (1") pieces. These pieces were sold as a landscape fill material for playgrounds. To make this process economically attractive, government entities collected a tire disposal fee, which was used to offset tire collection costs.

The next phase of research focused on the use of these tire pieces as a fuel, either alone or combined with another solid fuel. Current NAAQS limit emissions of sulfur oxides. In some areas, burning tires alone emits more SO_x than allowed by permit. The alternative is to either mix the tire chips with a low sulfur fuel and/or to install costly pollution controls, such as flue gas desulphurization equipment. Continuous emissions monitoring provides a record of emissions in real time. Plant operators can adjust the conveyor speed and fuel mix to minimize exceedances.

2.4 Additional Topics for Research

Resource Conservation and Recovery Act (RCRA), 40 CFR Part 264 Subpart O-Incinerators, 40 CFR Part 265 Subpart O-Incinerators, PM10, PM2.5, Haze, Landfill, Recycling, Carcinogen, Pulmonary diseases, Regional Haze Program, RIO Plus 20, Road ecology, Aquaponics, The Dune Trilogy, Appalachia, CO Monitors, Gypsum, Sorbents, Electrostatic precipitators, Dust cyclones, Bag house, Thermal oxidizers, Particulate scrubbers, Catalytic reduction, Vapor recovery systems, Abatement, Flue-gas desulphurization, Continuous emissions monitoring systems, Carbon capture, Coal gasification, “Clean coal” technology, Octane, Greenhouse gas, Marcellus shale, Barnett shale, Mitchell Energy, Fracking, Landfill gas, Coal gasification, Flares, Refinery, Keystone Pipeline, Trans-Alaskan Pipeline, North Slope, Valdez, Sulfur, SO_x, NO_x, Peak oil, British Thermal Unit (BTU), Igor Sikorsky, Hoppers, Avgas, Diesel fuel Toxic Substances Control Act, National Emissions Standards for Hazardous Air Pollutants, (NESHAP), Leachate Vulcanization, Rubber, Permit to emit, Title V, West Nile Virus, Malaria, Yellow fever, Disease vectors.

2.5 Assignments

1. What is the impact of the ethanol mandate on land use? The states producing corn for fuel are not able to use their land to produce other crops. Does this lead to a food shortage in those states? Explain.
2. As grain is shipped out, some foods are imported. Most farmers have a family vegetable garden. People in urban areas generally buy their food from grocers. Are fresh foods less available or shipped further because of the ethanol mandate?
3. Has the ethanol mandate affected the price of cane sugar? Beets? What is a sugar cartel?
4. If more fats and oils are diverted to produce biodiesel, the supply of what other products may be affected?
5. Ladybird Johnson, the wife of US President Lyndon Johnson, urged the passage of the 1965 Highway Beautification Act. How has the Act encouraged the cultivation and preservation of native plant species in your neighborhood?
6. United Airlines allows passengers to purchase credits to offset the CO₂ emissions attributed to their air travel. Who gets this money and how is it used?
7. Why are plant materials and yard wastes banned from sanitary landfills? Name three revenue-producing uses for these solid wastes.
8. Does your community collect and compost plant materials and yard wastes? What happens to the compost?
9. Why do municipalities value trees? Provide six reasons for planting trees in urban areas.

10. What is Methane clathrate? Where does it exist on earth? What problems are associated with its use as a fuel?
11. Summarize the myth and the reality that the Zionists made the desert bloom in Israel. How and where could those lessons learned be applied today?
12. What is the purpose of the organization “ILoveMountains.org”? How many of the supporters actually live in Appalachia?
13. What is black lung disease? Is there a cure?
14. Which is safer for miners, strip mining or shaft mining?
15. Describe three technologies to use coal for energy.
16. Research the profitability of utility companies that provide electricity in your state. The price they charge for electricity is limited by the Public Utilities Commission. How much is the dividend per share of stock?
17. The USEPA on September 20, 2013 proposed regulations to limit CO₂ emissions from power plants by requiring carbon capture and storage (CCS). The intention is to force operators of older coal-fired plants to retire those facilities, reducing electrical output by approximately 40% with an accompanying increase in utility rates. What is the state of the science of CCS? What geologic conditions are required to implement it?
18. The typical electric utility bill contains a charge for the electricity used plus taxes and fees. In some regions, the price of energy is higher during peak hours. Examine a local electric bill. How much of the bill covers the cost of the electricity? What is the purpose of the taxes and fees?
19. What is lignite and how is it different from bituminous coal? Where are different types of coal found? Compare the heating value in BTUs of coal to other fuel sources (biofuels and fossil fuels).
20. The USEPA has proposed a national regulation that requires carbon capture and storage for coal-fired plants. Utility XYZ is not affected by the regulation because it operates natural gas-fired plants, municipal waste incinerators, and a windmill farm. Utility provider DEF opposes the regulation. Utility DEF is operating several coal-fired plants, a hydroelectric facility, and a nuclear reactor. Utility XYZ serves a densely populated region that is flat, windy and has large reserves of natural gas. Utility DEF serves a sparsely populated mountainous region with ample coal reserves and several swift rivers. The citizens in the region served by Utility XYZ voted for the current administration. The citizens in the region served by Utility DEF voted for the opposing candidate. Discuss the ethics of the proposed regulation.
21. CASE STUDY A rural mountainous community in West Virginia owns a parcel of land with a large deposit of coal. A company in Germany wants to buy the coal for export to Germany because the Russians are threatening to disrupt their supply of oil. The deposit is located near the surface, making strip mining the most economical method to harvest the coal. The company promises to comply with all environmental restrictions. Once the coal is removed, they will develop the parcel for civic and commercial activity. The citizens support the proposal. An outside group opposes it; they want the land to remain undeveloped, but have not offered to buy it. On the worksheet, Fig. 2.1 list the pros and cons of this proposal. Should the town risk a lawsuit from the outside group?

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Heckel, P.

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