

FOSSIL-FUELED CIVILIZATION

Heat and Motion

Engine. An engine converts heat to motion. A *steam engine* does so by using steam—water in its gas phase. Many designs of steam engine exist. They operate according to phenomena known to ancients. Heat turns water into steam, the steam expands, and the expanding steam moves things.

Our subject—thermodynamics—originated from the development of engines in the Industrial Revolution. Kelvin (1850s) coined the word “thermodynamics” from a hybrid of two words: “thermo” means heat, and “dynamics” means motion.

A transformative invention. The engine was a transformative invention two hundred years ago, just as the Internet is one today. The enthusiasm for engines is evident in the small book, *Reflections on the Motive Power of Fire*, written by the founder of our subject, Carnot (1824).

Nature, in providing us with combustibles on all sides, has given us the power to produce, at all times and in all places, heat and the impelling power. To develop this power, to appropriate it to our uses, is the object of heat engines.

The study of these engines is of the greatest interest, their importance is enormous, their use is continually increasing, and they seem destined to produce a great revolution in the civilized world.

Already the steam engine works our mines, impels our ships, excavates our ports and our rivers, forges iron, fashions wood, grinds grains, spins and weaves our cloths, transports the heaviest burdens, etc. It appears that it must some day serve as a universal motor, and be substituted for animal power, waterfalls, and air currents.

In three short paragraphs, Carnot noted that

- Nature has many things to burn.
- Engine converts heat to motion.
- Engine revolutionizes the world by doing many things.

Hero’s toy. In the first century AD, Hero of Alexandria described a toy. A fuel (most likely biomass, such as wood) burns. The fire heats water in a boiler into steam. The steam expands through two pipes into a sphere, and escapes as two jets. The force of reaction rotates the sphere.



Demonstration. Bring to class a cup of hot water, along with a small engine. Place the engine on the cup of hot water, and let the engine run during the class.

The engine converts heat to motion—the rotation of a wheel. In this design, steam is not needed. We just need something hotter than the environment. Indeed, this engine is originally designed to operate with the difference in the temperature between your palm and the environment. See the description of the engine from the supplier (Low Delta T Stirling Engine, PASCO SE-8576A).



Motion and Electricity

Despite all the uses raved about by Carnot, the engine has an essential limitation: the output of the engine is motion. Our modern life, however, runs on electricity. Electricity lights up evenings, keeps refrigerators on, and turns washers. Electricity can be produced in one location, and then sent to another location through transmission lines.

The engine converts heat to motion. We need another transformative invention to convert motion into electricity.

Generator. A generator converts motion to electricity. An *electromagnetic generator* operates according to the law of induction, discovered by Faraday in 1831. When a magnet is moved, the motion *induces* an electric current in an electric circuit nearby. Read *The Feynman Lectures on Physics* (Volume II, Chapter 16). They are accessible online.



Demonstration. Bring a generator to class. The movement of my hand rotates a disk. The rotation induces an electric current in an electric circuit. The electric current lights up a bulb.

Heat, Motion, and Electricity

Steam power plant. The principles of Hero's toy and Faraday's generator are preserved in modern steam power plants. Simply put, a steam power plant runs a steam engine and a generator together. A fuel turns water into steam, the flow of steam rotates a turbine, and the turbine drives an electromagnetic generator. Thus, a steam power plant converts heat, via motion, into electricity.

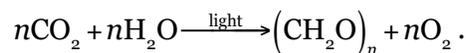
Steam power plants mostly use fossil fuels—coal, crude oil, and natural gas. You must have heard that we are addicted to fossil fuels, and that this addiction harms the environment. The topic is too hot—too political, economical, environmental, and emotional for this course. Rather, we will focus on something cool—something mathematical, physical, chemical, thermal, mechanical, and electrical.

Coal-fired plant. A coal-fired plant converts coal to electricity. A large plant generates electricity at the rate about 5 GW. It can supply electricity to 5 million homes, assuming that a home consumes electricity at the rate of 1 kW.

From the Sun to Electricity—A Detour

We now picture how the Sun helps coal form, as well as how a coal-fired plant turns coal into electricity.

Photosynthesis. In the beginning, there were the Sun, the Earth, and the Life. In photosynthesis, plants use sunlight to split water, produce O₂, and fix CO₂ to carbohydrates:



This reaction is studied in biochemistry.

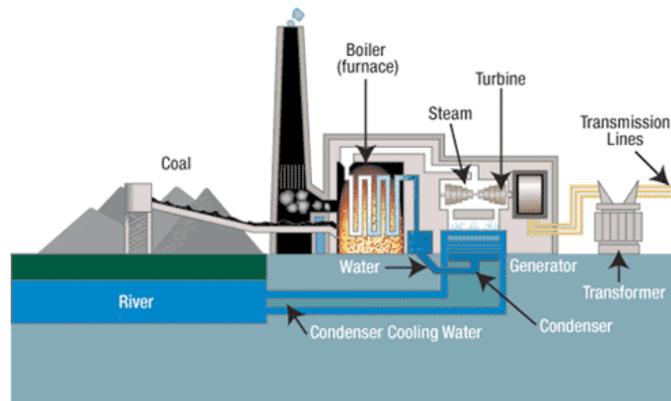
Coal. Then came the Flood. Water and soils buried the plants, deeper and deeper. The burial subjects the dead plants to high pressure, high temperature, and low oxygen. The conditions were just right to convert the dead plants to coal—fossil that contains mostly carbon.

Coal burns in a firebox. Coal meets oxygen in a firebox and burns. This chemical reaction is known as combustion, and is studied in chemistry. Combustion is also an area of application of thermodynamics.

Boiler turns liquid water into steam. As the fire heats up water, water turns from liquid into steam, and the same amount of water molecules occupies more volume. The expansion pushes everything around. This process historically motivated the creation of thermodynamics. We will return to this process repeatedly. Of course, the boiler requires materials to function in extreme conditions of high pressure and high temperature. This subject is studied in solid mechanics and materials science.

Flowing steam rotates a turbine. Waterwheels and windmills were invented in antiquity. Toy windmills bring fond memories of childhood. These devices are now called *turbines*. A turbine consists of a shaft and a set of blades. As a flowing fluid hits the blades, the shaft rotates. The turbine converts the flow of fluid the rotation of shaft. This conversion is studied in fluid mechanics.

Turbine rotates generator. Faraday (1831) discovered that a varying magnetic flux generates an electromotive force in a coil of electrical conductor. A generator consists of magnets and coils of electric conductor. As the turbine turns, the magnets rotate relative to the coils, producing electric current in the transmission lines. The conversion from motion to electricity is studied in electrostatics.



(<http://www.tva.gov/power/coalart.htm>)

From the Sun to Electricity—A Direct Route

The long march from the Sun to electricity is a detour. Our civilization has been developing more direct routes to use sunlight to generate electricity. In class I briefly describe solar cells and lithium-ion batteries. A solar cell converts sunlight directly to electricity. A lithium-ion battery stores electricity. These devices are described in courses in applied physics.