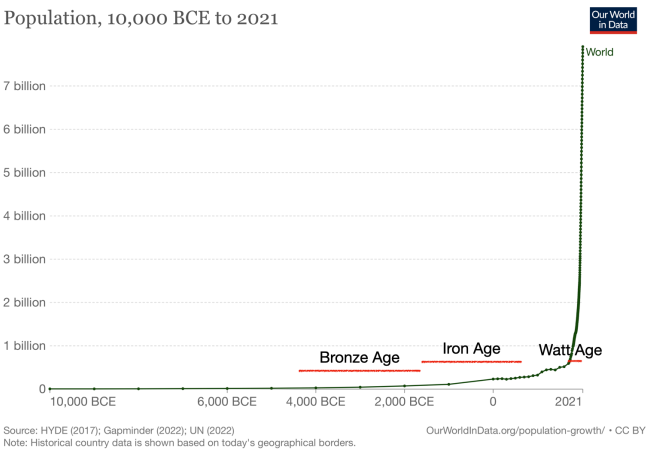
Energy for civilization

Civilization evolved via heat and work

World population had been relatively stable, under 4 million people, through a million years of history up to the start time of this graph, 12,000 years ago.[1] Population began to increase a bit during the Bronze Age, then more rapidly during the Iron Age. Population spiked during the industrial revolution, termed here the Watt Age, to honor Watt's development of converting heat to work. Note that the graph's horizontal axis change of scale at year zero, else the spike would look even steeper.



World population history

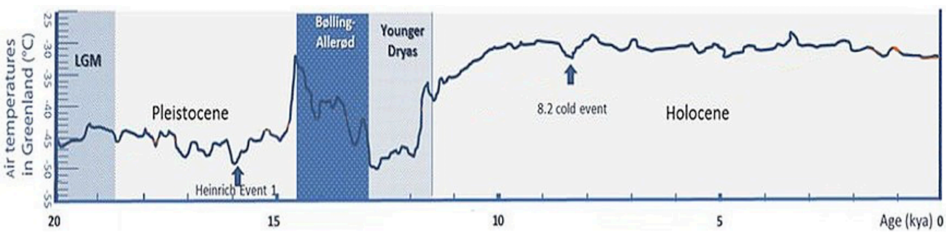
Heat energy

Human ancestors discovered how to control and use fire perhaps a million years ago. Controlled fire provided light and warmth. Fires at cave mouths frightened away predators.

Humans ate plants and animals for energy. Sunlight was another heat energy source, reducing demand for energy from food metabolism; reptiles use this source extensively.The big breakthrough in energy technology for humans was fire. Fire provided alternative energy to metabolism of food. Upright humans learned to use the heat of fire for cooking. Cooking food saved time and energy. Today's primates still spend half their day chewing raw food.

By switching to cooked, softer, more energetically rich food Homo Erectus was able to devote time to more productive activities, making tools, farming, and interacting socially. Reduced kinetic energy demands for metabolism permitted evolution of the human's large brain, which today consumes a quarter of the body's energy. Fossil records show the evolution to larger brains and smaller guts, jaws, and teeth.

By 50,000 years ago humans had developed tools such as fishhooks, spears, and techniques for cooperative hunting of large game animals. Stone age roving bands subsisted on hunting animals and gathering food.



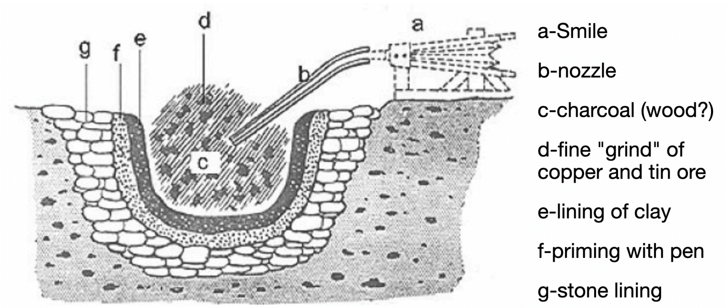
Climate warming in 10,000 BC enabled agriculture[2].

Agriculture was invented approximately 10,000 years ago as food from hunting and gathering became more difficult, possibly due to the end of an ice age, creating a dryer climate.[3] Dry conditions favor annual plants, which store energy in seeds rather than woody, perennial growth. Cereal seeds' energy density made them an attractive food, but their shells limited digestibility by humans.

Another invention of the time was grinding seeds into flour, which was made into bread. Bread's ground seed flour, fermentation, and cooking made an easily digestible, transportable, storable food energy supply. Bread sustained people, allowing them to live in villages and cities rather than dispersing for hunting and gathering. Productive agriculture enabled storage of food and freed time to make more tools, build shelters, develop writing, and advance civilization.

Bronze Age

5,000 years ago humans learned to make bronze metal from copper and tin. They used 1100°C heat and charcoal's carbon to remove oxygen from copper and tin ores.[4] Bronze was stronger than copper.



3000 BC 1100°C furnace for melting copper and tin[5]

Iron Age

Killick: A 2.2 m well preserved, natural draft, iron smelting furnace in Kasungu National Park, Malawi

About 3,000 years ago iron become available to humans. Iron is stronger than bronze and iron ore is plentiful. 1250°C heat can reduce iron ore to iron bits that could be pounded together, forged, to form “wrought iron”. Even hotter heat up to 1535°C was needed to to free iron from ore and cast iron into parts for machines or tools. African hardwoods and charcoal could burn hot enough in vertical furnaces with natural draft.[6] Adding carbon lowers iron melting point to 1150°C, but the iron is brittle.

Lesson: Hotter heat improved the technology to extract metal from ore. The hotter heat enabled civilization to use stronger, more plentiful iron rather than bronze or copper metal.

Work energy

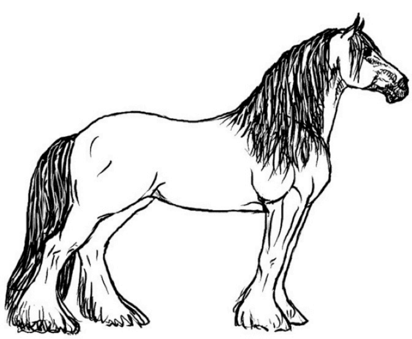
Civilization needed work energy. Physical work was essential for throwing spears, scratching seeds into the ground, carrying food home, or cutting hides off deer to make warm clothing. Slaves provided labor work in the Roman empire, which obtained them by war, piracy, trade, and slave births. Humans were an inadequate source of work, so draft animals were developed and used.

Work is force applied over a distance. Work can be converted to gravitational potential energy by a horse lifting water from a mine, or just to heat energy produced by friction if the horse is pulling a sledge.

Power

Power is the flow of work energy, energy transferred per second. Power is measured in watts. One watt flowing for one second is one watt-second (joule) of energy. One watt flowing for one hour is 60x60 watt-seconds, one watt-hour (Wh).

Always carefully distinguish Power (Energy/second) and Energy (Power x time), often confused by reporters.

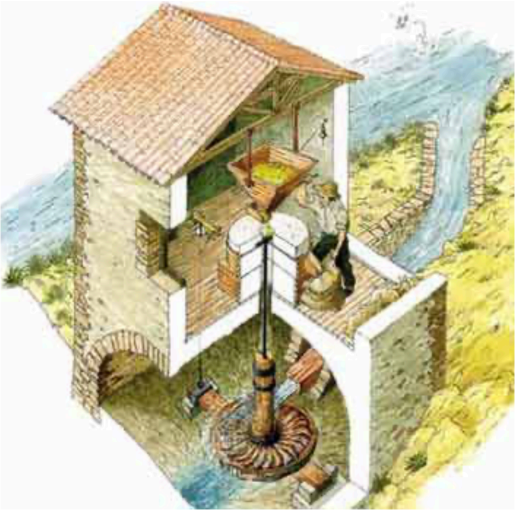


Lifting a weight of 550 pounds up one foot requires 550 foot-pounds of work (in old imperial units). The standard English rate of work for a horse hauling water up from a mine was 550 foot-pounds per second, defined as one horsepower. James Watt used this definition to account for 33% royalties for his horse-substituting steam engine.

One horsepower (hp) is 746 watts. A related unit of energy is the horsepower-hour, one hp applied for one hour. One hp-hour is 0.746 kWh, about ten cents worth of electricity today – much cheaper than power from horses. A bicyclist in good condition can generate about ¼ horsepower, just over 200 watts. If humans were paid competitively to electricity for their physical work they would receive 2.5 cents/hour.

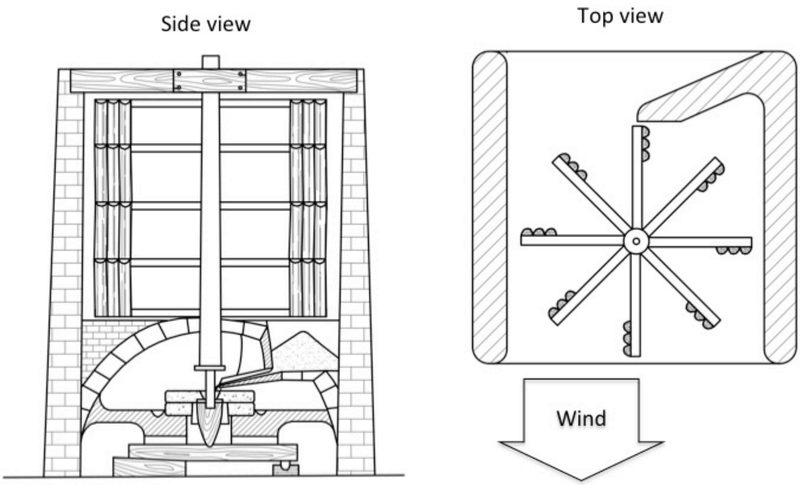
Work from water and wind

Climate change 10,000 years ago favored annual plants, which store energy in seeds rather than woody, perennial growth. Their energy density made seeds an attractive food, but their shells limited digestibility by humans. So another great invention of the time was grinding seeds into flour, which was made into bread. The grinding, the fermentation, and the cooking made an easily digestible, transportable, storable food energy supply that sustained people living in villages and cities rather than dispersed people for hunting and gathering.



Early French water powered grain mill[7]

Milling grain had required human energy expenditure and time. An important new energy invention was the use of water power to mill grain. Early millstones were rotated horizontally, about a vertical shaft, which can be powered efficiently by a horizontal water wheel. Friction losses were minimized because there were no gears. The farmer at the top red grain into a hopper. The top millstone rotated to grind seeds into flour. More familiar vertical water wheels came into use after efficient gears were invented.

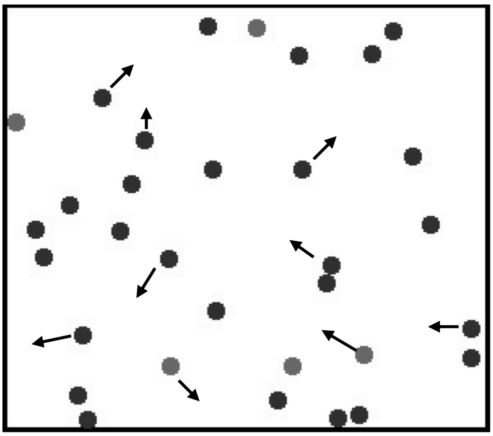


10th century Persian horizontal windmills[8]

Early windmills were constructed to rotate about a vertical axis. This windmill design is from 10th century Persia. They were used for milling grain and pumping water. More familiar windmills with blades rotating in a vertical plane on a horizontal axis facing the wind were developed after low friction gear technology was able to transfer the kinetic energy.

Work from Heat

Work is different from heat. Both are kinds of energy. Moving molecules each have kinetic energy proportionate to their mass times velocity squared. Heat energy is the sum of the kinetic energies of many, many moving molecules.



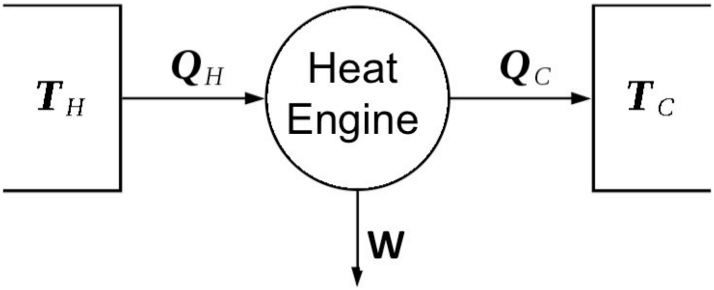
Heat: the kinetic energy of molecules

Kinds of useful energy (with examples) include chemical potential energy (gasoline), gravitational potential energy (water behind a dam), electrostatic energy (in a capacitor), magnetic field energy (in a transformer), and electromagnetic wave energy (of a photon). Work is the physics term for the useful energy to move something agains a force (pulling a plow through a muddy field). Along with kinetic energy these useful energies can generally be converted from one form to another with low losses.

Converting work to heat is easy; the friction of rubbing your hands together heats them. Converting heat to work is hard; we can only extract work by harnessing the flow of heat from hot to cold. The processes that convert work to thermal heat are not 100% reversible. Physics will not let us convert all that thermal energy back to kinetic energy, or work.

However we can convert some of the heat flowing between objects of different temperatures. Heat flows from hot to cold as heat's molecular motion is dissipated into a larger, cooler system.

If we do nothing, this heat flow is totally wasted. Alternatively, we can insert a heat engine into that heat flow and extract some (but not all) of that heat energy into work (W).



Heat source, heat engine, heat sink

T_H is the temperature of a source of hot heat energy.
Q_H is the quantity of heat going into the heat engine.
W is the useful work extracted by the heat engine.
T_C is the temperature of the heat sink. $T_C < T_H$
Q_C is the quantity of rejected heat flowing into sink.

In an automobile engine, Q_H is the heat generated by burning gasoline, W is the work delivered by the rotating crankshaft, and Q_C is the heat lost to the atmosphere via the cooling radiator and the exhaust pipe. Other examples of heat engines are Watt's 18th century steam engine and an aircraft turbine jet engine. They convert some heat to work.

Sometimes the rejected heat Q_C is prejudicially termed waste heat, but the thermodynamic process is a fact of physics. T_H and T_C are measured in °K, degrees above absolute zero, -273°C.

Heat to work conversion efficiency is always < 1. Energy in equals energy out, so $Q_H = Q_C + W$. By Carnot's theorem[9], no matter what engine is devised, physics limits conversion efficiency to be less than 1.

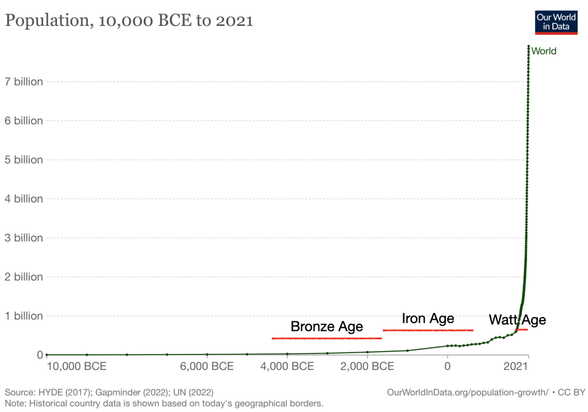
$$\text{Efficiency} = \frac{W}{Q_H} = \frac{T_H - T_C}{T_H} < 1$$

The formula shows that the higher the temperature difference between source and sink, the better the efficiency. Increasing the heat source temperature is one way to increase efficiency. Decreasing the heat sink temperature also increases efficiency. River or ocean water can absorb more heat more quickly than can air, so waterside power plants can convert more fission heat to electric energy and less to rejected heat.

Rudolph Diesel's 1896 invention of a high-compression, high-temperature internal combustion engine had a theoretical maximum kinetic/thermal energy conversion efficiency of 75%, compared to 10% for the competitive steam engine, making him a millionaire. Large shipboard diesel engines can achieve over 50% efficiency. In practice the typical efficiency of an automobile diesel engine is 40-50%. It burns fuel at a higher temperature than a gasoline engine with its 30-35% efficiency. The reciprocating steam engines of the 18th century had efficiencies near only 1%. Today's steam turbines heated by 550°C steam can reach 47%.

The Watt Age: Heat in Harness

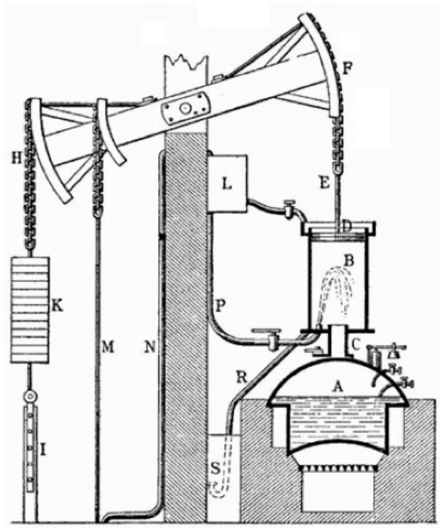
The *World population history* figure, repeated below, indicates how slowly world population grew for thousands of years, even after the discovery of iron for strong tools. Population boomed starting with what we now call the Industrial Revolution launched 250 years ago.



World population history

We deem the period starting around 1776 to be the Watt Age, when Watt began the improvements and commercialization of the steam engine. The sudden bounty of ample work energy created from heat that has sparked two centuries of civilization advancement. We owe the industrial revolution to the invention of work from heat.

England's people had denuded forests for wood for heat in the 18th century, increasing demand for coal available in near-surface seams. As miners dug deeper water seeping into the mines needed to be removed, laboriously. Early inventions by Savery and Nucomen put hot steam in a cylinder which was then cooled to create a vacuum pulling a piston.



Newcomen's 1712 steam engine

Watt continually improved the design, using steam pressure instead of vacuum, and the steam engines replaced water wheels and horses.

Transforming heat to work was the technological breakthrough that launched humanity onto its rapid, two-century path to today's peak civilization. People had used their iron tools, forges, swords, and cannons for thousands of years while hardly advancing civilization. Suddenly the steam engine provided inexpensive, ample work energy and unlocked progress.

Extensive coal mining became possible because of steam engines that pumped water from the mines and lifted coal to the surface. Steam engines enabled factories to be built where no water power was available. They pumped water into canal locks to facilitate transportation for growing trade. Mined coal powered boats and trains, provided heating, and burned hot enough to smelt iron. Iron and steel, stronger than copper or bronze, enabled better machines to be built. Lathes and other metal working machine tools were fabricated.

Heat from plentiful coal helped advance the chemical industry, enabling production of sulfuric acid and sodium carbonate used in the glass, textile, soap, and paper industries. Very hot heat of 1600°C sintered ground limestone and clay into Portland cement for construction.

Paper mills powered by heat energy and work energy provided plentiful, inexpensive paper for publication of books, helping spread knowledge. Canals, roads, and railways were built and used for commerce, including hauling coal.

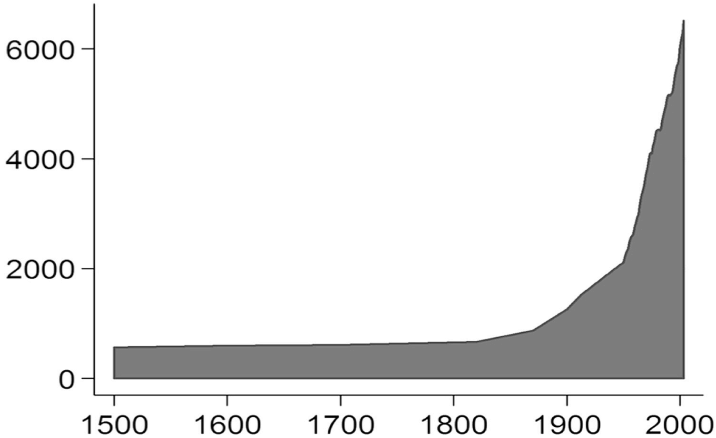
Converting heat to work

External fuel combustion made steam heat to create work energy at efficiency less than 4%. After1870 internal combustion engines were developed to burn fluid fuel within cylinders and convert heat to work at efficiencies exceeding 14%. Modern gasoline engines in automobiles reach efficiencies near 40%, and diesel engines near 50%. Airplanes fly with onboard fuels burned and converted to work energy to rotate propellers. The modern jetliner turbine engine has a work/heat efficiency in the 20-40% range. Keep in mind Carnot's theorem limits the efficiency of converting heat to work.

$$\text{Efficiency} = \frac{W}{Q_H} = \frac{T_H - T_C}{T_H} < 1$$

For example, a nuclear reactor might be the source of 704°C heat. Relative to absolute zero, -273°C, that's 977°K on the Kelvin scale, where temperature is proportional to energy. Suppose 20°C (293°K) seawater is an available heat sink. The maximum possible heat-to-work conversion efficiency is (977-293)/977 = 0.70 = 70%. *New nuclear* manages 46%.

The industrial revolution spread from the United Kingdom to Western Europe, North America, Japan, and the world. In two centuries the world average per capita income increased tenfold. Since 1820 world population has increased five times. Lifespans have more than doubled. Angus Maddison illustrates[10] world GDP per capita growth rate growing at the time of the industrial revolution and coal energy.



Madison: World GDP per capita in 1990 international dollars

Heat to Work to Electricity

The Watt Age began about 1776, and Benjamin Franklin discovered electricity in 1752. In 1831 Michael Faraday invented the electric generator that changed the kinetic energy of a rotating mass into electricity. In 1882 Thomas Edison established the coal-fired Pearl Street electricity generating station in New York City. The conversion efficiency between kinetic energy (work) and electric energy can be near 99%.

Electric energy is useful energy that can be directly converted to work, such as kinetic energy or to gravitational potential energy. The notation Wh(e) distinguishes useful, electric energy from Wh for heat energy.

Though James Watt never conceived of electricity, we associate “watt” with electric power and abbreviate it “W”. It’s also a measure of heat flow or any type of energy flow; we write W(e) for electric power if there is ambiguity. Watts are joules/second, J/s. Today the developed world depends intensely on electricity, with average global power consumption being 3,000 GW(e), or 3,000,000,000,000 W(e).

Earlier we saw that Carnot’s heat flow analysis indicated that the hotter the heat source, the more work (or electricity) can be extracted from heat flow. Hotter heat can also speed up chemical processes. Hotter heat sources will make electricity cheaper. Concentrated solar power focused by fields of mirrors can generate 565°C heat, but the only reliable CO2-emissions-free source for hot heat is nuclear power, and *new nuclear* technologies provide the hotter heat. *New Nuclear* is HOT!