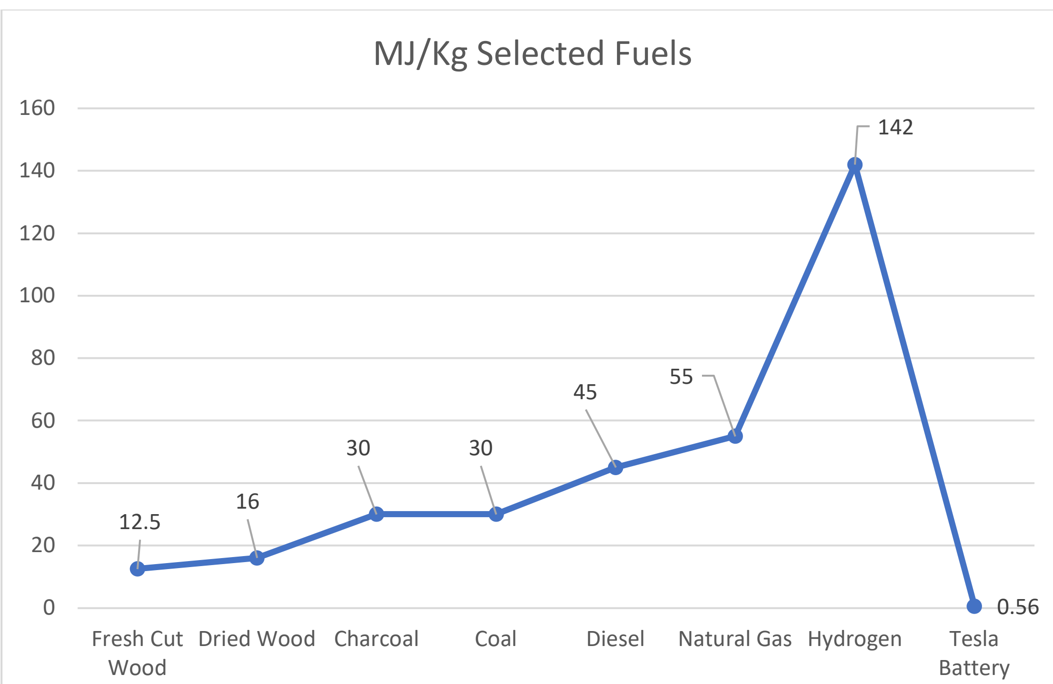
Energy Density, Carbon Density, and Ease of Use

A study of energy usage through history is very enlightening. Not only does it tell us about what humankind has done with energy in the past, but it informs us about what we are likely to do in the future. In large part, this discussion is inspired by 'Energy in World History' by Vaclav Smil, written in 1994. He has written a followup to this book in 2017 called 'Energy and Civilization; a History' which came out in 2017, but I have not read it.

Quick – which would you rather have? The sunlight shining on a meadow for a day, the waves on a beach, or a gallon of gasoline? Given equal energy content, most of us would choose the gasoline, because it's got the highest energy density, you can easily move the gasoline from one place to another, and use it to power a wide range of devices and perform a variety of work. , high density, flexible energy sources which are safe and easy to use are the ones which make modern life possible. Harvesting and using diffuse sources of energy like sunlit fields or waves requires tremendous effort to organize, concentrate and direct.

Energy Density

As technology has advanced the use of energy has moved from diffuse sources, to concentrated sources. In terms of agriculture and the natural world this has been a movement from gathered foods, to farmed plants, to farmed animals, and at each step in the process, there has been a concentration of energy into more useful forms. In terms of fuels, it has been a movement from dung, to wood, to charcoal, to coal, to oil, to electrical, and nuclear power. The improved amount of energy available from each source is clear.

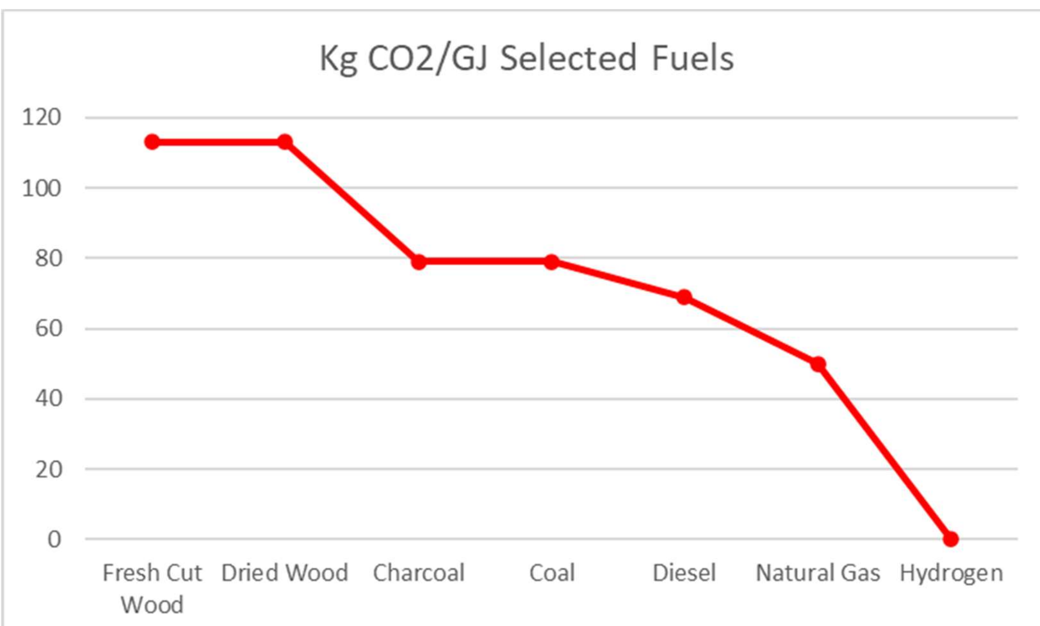


Adapted from https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

Note the extremely low energy density of the Tesla battery – it's around 80 times less energy dense than diesel fuel. Even when accounting for the fact that hydrocarbon fuels are usually used at an efficiency of around 35% due to thermodynamic constraints this is still a tremendous difference. Electricity is an excellent way to move energy from one fixed place to another, but it cannot readily be stored or moved to and from unexpected places. The potential of hydrogen as a fuel is obvious. Pure Uranium 235 is not on the chart because it comes in about 2 million times better than natural gas, and won't fit on a chart like this. Despite all the other problems (and there are many) this explains the tremendous attraction that nuclear power has as an energy source. Wind and solar electrical power production are both methods which convert diffuse energy (wind and solar energy) into concentrated ones (electricity).

Carbon Density

Coincident with the movement towards systems with a higher energy density has been a movement towards fuels with a lower carbon density. This movement started well before any modern concerns about CO2, for other more immediately practical reasons. Burning wood generates large amounts of smoke and leaves a lot of ash. Charcoal is better, but it requires 5 to 7 times as much wood by weight for each measure of charcoal. Coal has considerable amounts of impurities, requiring extensive measures taken to remove ash, and prevent fouling of grates and other equipment used to burn it. Solid fuels suffer from increased difficulty in moving them around as well. Petroleum products produce considerably less of a mess than coal, and natural gas burns clean, without any ash, heavy metals, sulfur or other debris left behind. Hydrogen doesn't even produce CO2 when it is used for combustion processes.



Adapted from https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html

Ease of Use

Ease of use requires 3 things in an energy source: the ability to store it, the ability to move it around, and the ability to use it safely. The previous two graphs should make clear something that may have already been intuitive if they were not before: high density, low carbon sources of energy are convenient to use. Gaseous fuels like natural gas and hydrogen suffer because while they have high energy density per kilogram, and low carbon emissions, they are not generally speaking available to be carried around in small containers to wherever they may be needed. This explains why natural gas tends to be concentrated for use in electricity generation and in large scale industrial processes – while it's got a lot of advantages, it's hard to move around from one place to another without a dedicated fixed infrastructure to make it possible. Nuclear power doesn't have portability, and has questionable safety issues.

Electricity as a method of powering portable equipment, be it cars, ships, aircraft, riding mowers or anything else is a massive challenge. Trains are an exception to this. Because they follow fixed routes on their rails and fixed routes ONLY they can and often are set up with dedicated electric supply systems. For a long time now, there have been expectations that batteries would eventually allow us to set electrically operated equipment free to roam around the world. However, this is not happening to any significant degree yet. The Tesla 3 is a marvel of modern battery technology, and the long range 480 kg battery pack has within it the power equivalent to 6 kg of diesel fuel. Burned at 35% efficiency, this is equivalent to about 21 liters/ 6 gallons. This is acceptable for a lightweight passenger vehicle. However as the vehicle gets heavier, or intended for longer range operation, the fraction of fuel required to operate it gets larger at a higher rate than the weight of the vehicle and powertrain does. For example, for a standard 18 wheeler rated at 80,000 lbs/36,000 kg total weight with an empty weight of 36,000 lbs/16,000 kg and which can carry 44,000 lbs/20,000 kg of goods running 10 hours a day will burn ~ 80 gallons/300 liters of fuel a day weighing in at ~ 240 kg. Using our 35% efficiency factor for the fuel burn rate, and our 80 to 1 ratio of energy storage per unit weight between diesel and tesla batteries, replacing this with a battery will require a battery that is ~ 6,000 kg – This reduces the weight available for cargo by ~ 30% a major negative factor.

Future Trends

Electricity is a wonderful method of transmitting power from one place to another, and there are plenty of clean non CO2 emitting ways of making it which are price competitive – nuclear power, hydroelectric power, wind and solar energy are all great examples. Wind and solar power production techniques have successfully transferred diffuse non CO2 emitting sources of energy into concentrated ones and critically look to be easy to scale up at current economic prices but have not successfully made that electric power available on demand, storable, or portable – i.e. easy to use. Electrification of our economy offers the easiest way to decarbonize, but it runs directly counter to the need for energy on demand and storable and portable sources of energy. The elimination of carbon emitting sources of electric power for stationary power requirements is almost assured to happen, and happen soon, but doing the same for portable use will be dramatically more challenging. Batteries which are roughly 2 or 3 times more efficient than the ones that we have now and at a reasonable cost would probably be required for a full transition by solving the ease of use problem for carbon free electrification of modern economies.