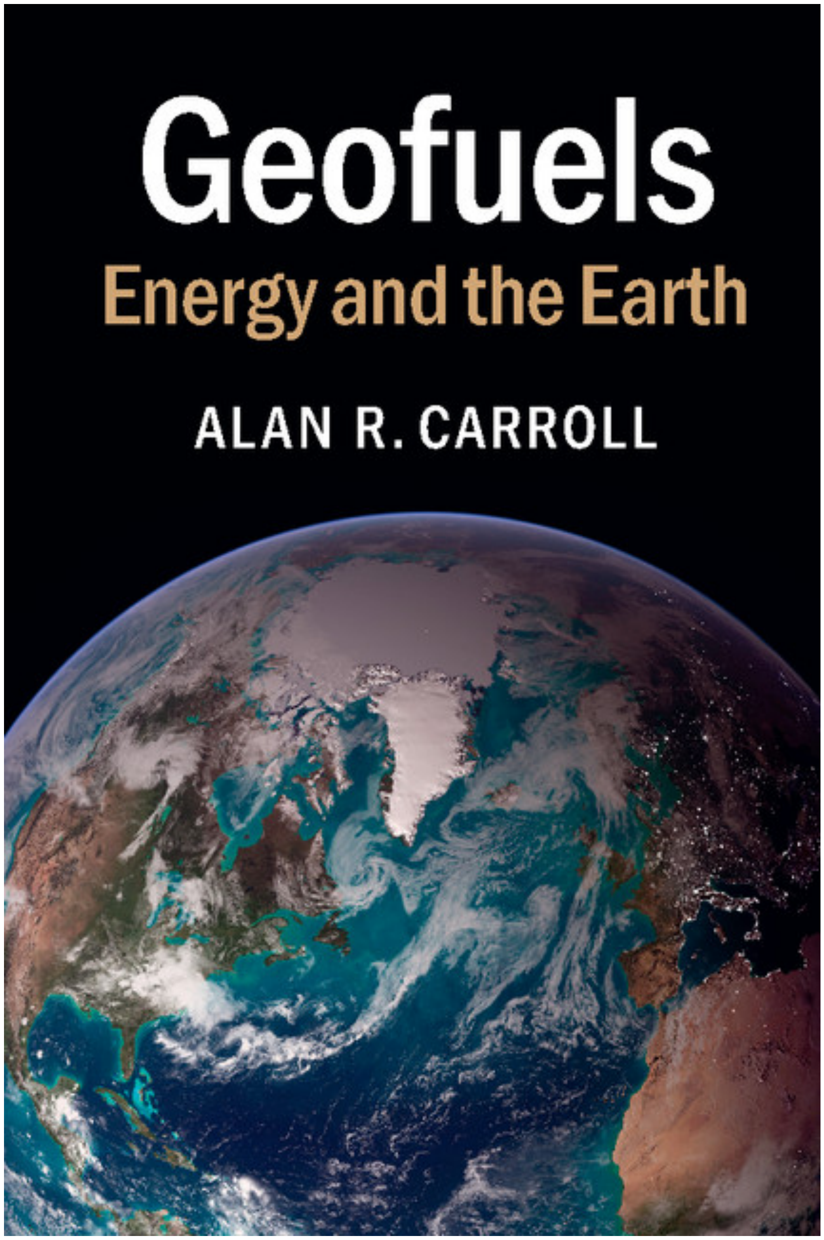
Warmed From Above: Solar Energy

Excerpts from “Geofuels: Energy and the Earth” by Alan Carroll



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Our local star has continuously bathed the Earth in sunshine for the past four and a half billion years, interrupted only by the occasional solar eclipse. The Sun is expected to continue shining for billions of years to come, setting a gold standard of sustainability that no other major energy source can hope to match. The Sun supplies the energy for all plant life, and therefore is also the source of energy contained in both biofuels and fossil fuels. The Sun also powers the weather, through solar heating of the ocean and land surfaces. Hydroelectric and wind power are really just cleverly disguised versions of solar power. In fact, only two presently used energy sources can claim true independence from the Sun: nuclear fission and tidal energy. Nuclear fission relies on uranium, an element forged in the violent explosions of other, more massive stars called supernovae. Tidal energy results from the gravitational pull exerted on the ocean by the Moon, and to a lesser extent the Sun.

As powerful as it is, one thing the Sun cannot do on its own is to boil water at the ambient conditions found on the Earth's surface. At high noon on a clear day at the equator, sunlight heats the Earth's surface at a rate that is roughly equivalent to a portable electric hair dryer aimed at an average-sized desktop. The desktop (or ground surface) becomes warm, but not painfully so. At all other locations on the Earth the average rate of incoming solar power is less, because of clouds or a Sun angle that is less than 90° relative to the horizon. Nowhere on Earth is it ever really hot enough to fry an egg on the sidewalk, a fact that can easily be demonstrated through independent study. It's a good thing, too, because otherwise the oceans would boil or evaporate, and the entire planet would be permanently cloaked in dense clouds. Viewed from the Moon, the Earth would look like a white pearl rather than a blue marble.

The constant rotisserielike movement of the Earth around its axis presents a major inconvenience for solar power production, because half of the globe is always kept in the dark. Some type of energy storage system will therefore always be required to take advantage of sunshine, after the Sun stops shining. On the other hand, the huge surface area of the Earth means that the total amount of solar energy striking it is immense, more than eleven thousand times our current global power consumption. Of course, most of this sunlight total arrives in inaccessible locations such as oceans and mountainous areas, or else at high north or south latitudes, where it is too spread-out over the Earth's surface to generate much useful power. Even with these limitations, however, no other practical energy resource approaches the magnitude of solar.

Additionally, solar power produces no greenhouse gases or other negative environmental effects, at least in principle. Its potential is therefore impossible to ignore.

The Global Geography of Solar Energy

Clouds are the natural enemy of solar energy; they can reduce the total sunlight reaching the ground by factors of up to 80 to 90 percent. Fortunately our eyes and brains adapt automatically to these decreased levels of illumination; we may find cloudy conditions a bit depressing but we don't stumble around blindly for lack of light. Solar collectors, on the other hand, are immune to emotional disturbance, but have no choice but to downscale their energy output on cloudy days. The total amount of solar energy that is available at any given geographic location therefore depends in part on the local climate. Other factors being equal, Sun-scorched deserts will always out-perform overcast greenswards in terms of solar energy potential.

If clouds are the enemy of solar power, then deserts are its friend. On a year-round basis, deserts commonly receive twice as much sunlight as do more hospitable regions at similar latitude. This is not to say that useful solar power cannot be generated in cloudy regions; certainly it can. However, the same investment in solar collection systems would buy up to twice as much power output if they were installed in the desert (other factors being equal). This basic physical reality is hard to ignore and leads to the conclusion that solar power is to a large extent a geographically heterogeneous resource.

It is probably no accident that the English word "desert" can be used as a noun indicating a barren, desolate, or dry place, and also as a verb meaning to leave or abandon. The term in its former sense is commonly applied to areas with less than 25 cm/yr of precipitation; a more complete definition specifies that the potential for evaporation exceeds annual rainfall. Humanity has for the most part avoided such regions, preferring to leave them to lizards, nomads, fortune seekers, and persons prone to experiencing mystical visions. Lack of water may perhaps be responsible for some of those visions, and it strongly inhibits the development of major population centers.

(Un)Moved by the Sun

Even in the driest of low-latitude deserts solar energy is a gentle giant: immense in size, but never overly assertive. The diffuse disposition of sunlight imposes some intrinsic limitations on its practical use as an energy source, particularly with respect to converting solar energy into motion.

Steam offers a simple and inexpensive means of converting thermal energy into mechanical energy, taking advantage of the volume expansion that occurs when water is heated and vaporized. We tend to think of steam engines as outdated relicts of our primitive past, largely of interest to museums and certain railroad enthusiasts, but nothing could be further from the truth. Most modern electrical power plants use steam to drive turbines, which in turn drive generators. Today's cutting-edge computers and the Internet are for the most part powered by steam!

Steam turbines and all other heat engines are subject to certain inescapable physical limits on the efficiency with which they convert heat into motion. The thermal efficiency of an engine can be defined as the percentage of input heat energy that can be used to do useful work. Early in the 19th century the French physicist Sadi Carnot noted that the maximum possible efficiency of a heat engine is strictly governed by the temperature difference between an engine's hot operating fluid (burning gases, steam, or just hot air) and the cooler ambient temperature of its surroundings. In the case of a typical coal-fired electrical power plant, the operating fluid is pressurized steam or supercritical water, heated to temperatures near 400°C. The temperature of the cooling medium (air or water) might average around 15°C. This temperature spread gives a maximum efficiency, under ideal conditions, of around 54 percent. However, this ideal or "Carnot" efficiency really only applies to machines that are moving at an infinitesimally slow speed and fails to take into account various other unpreventable energy losses. In practice the electrical energy output of a typical coal-fired power plant amounts to only 30 to 40 percent of the heat provided by combustion.

Raw, unfocused sunlight at the Earth's surface cannot approach the operating temperatures of a coal-fired power plant. A more realistic point of comparison might be a minivan with a burgundy interior, parked at a suburban shopping mall near Phoenix, Arizona in July, at lunchtime. Lets assume the car's owner has left a small dog named Fifi sitting inside to repel any would-be intruders and closed all the windows. Fifi may ultimately expire from dehydration, but the dog will never burst into flame. The maximum temperature inside the car might reach 60°C, but will not exceed the melting point of the scorching vinyl seats (about 85°C). The temperature difference between the inside of the car and dry heat outside would therefore be only about 20°C–25°C. The *maximum* thermal efficiency calculated from this temperature difference is only about 8 percent, and the actual efficiency of a solar heat engine installed in the car would be much less than that. The car's hot interior would therefore be virtually useless for generating any appreciable motive force.

An alternative approach to solar transportation is to use photovoltaic cells to convert sunlight directly into motion, avoiding heat engines and their limitations altogether. Photovoltaics work by using sunlight to force electrons to move between two adjacent semiconducting materials, which most commonly are constructed by coating crystalline silicon with elements such as phosphorus and boron. The moving electrons can be used to operate an electric motor, which in turn can propel an automobile.

This idea looks great on the drawing board; after all, what's not to like about a car that needs no fuel and produces no emissions? Regular competitions are held between teams of university engineering students to produce just such a vehicle (the Solar Challenge), and these inspired students have produced many impressive designs, capable of carrying a single driver at reasonable speeds down a smooth road on a sunny day. Such a car would not satisfy the practical demands of most motorists, though, particularly those who prefer large sport-utility vehicles (SUVs). Some solar car designs bear a curious resemblance to a rolling slice of toast, with lots of flat upper surface area covered in photovoltaic cells. The driver's head often protrudes beneath a clear plastic bubble, like a dollop of jam on top of the toast.

The reason for this cramped seating is simple: There just isn't enough solar energy available to obtain the performance of an average car, much less an SUV. The mild nature of sunlight is once again to blame. A typical smallish car might have a surface of about 8 square meters, which on an ideal day in the Sahara desert might receive sunlight at the rate of about 1,000 watts per square meter, for a total of 8,000 watts. Converting units, this is equal to only about 11 horsepower (hp). As it happens, an actual horse can produce this much power for brief periods. The sporty Toyota Prius hybrid has about 80 horsepower on tap, and larger SUVs usually have at least 200. With some major scaling back of our expectations a practical 11 hp car might be possible, but at this point efficiency once again raises its ugly head. The actual electricity produced by photovoltaic cells mounted on a solar car will be only around 10 percent of the available solar energy. So rather than 11 horsepower you have about 1 horsepower at best, and most of the time you will have less. Perhaps it would make more sense to buy a living horse instead, learn to ride, and relive the halcyon days of the 18th and 19th centuries!

Wind, Water, and Waves: Energy from the Fluid Earth

Sunlight is abundant and free, and, but not particularly strong in its natural state. One potential solution to this problem is to produce concentrated solar energy by using mirrors to focus the sun's rays, an approach that is already being employed on a limited scale. Alternatively, we can let nature do the concentrating for us, by using the energy contained in wind, waves, and rivers. Sunlight causes dramatically unequal heating of the Earth's surface at different latitudes, between land and sea, and between night and day. Uneven heating sets air and water into motion, leading to a complex and sometimes violent sequence of events that act to spread warmth more evenly across the globe. These events never reach an end, however, because the Sun continues to shine and the Earth never stands still. We therefore experience perpetually dynamic weather.

Wind can thus be thought of as solar energy converted into motion. The interaction between wind currents and surface topography help to focus this flow, resulting in localized areas where surface wind speeds exceed the regional average. An opportunity therefore exists for the wind to do real work, if we are somewhat selective about where and when that work is to be done. This is of course no great revelation; wind has propelled sailing ships and turned windmills since the dawn of recorded history. However, wind has also developed a well-deserved reputation for inconstancy. Some days it arrives with a destructive vengeance that precludes any peaceable use; other days it fails to show up at all. Surface wind speed routinely increases during the daylight hours, but then drops off in the early evening, just as residential electric loads are ramping up. For wind to shoulder a large share of our primary energy load therefore requires that the impact of such lapses be ameliorated.

Wind also propels waves, by blowing over the surface of the ocean (or across a lake). The great majority of Earth's wind-driven wave energy lies beyond easy reach however, in the open ocean far from shore. It may be technically possible to recover wave energy from such distant seas, but it will likely require an elevated level of desperation before we actually attempt to do so. The situation is more encouraging near the seacoasts, in part because this is where much of the world's population lives.

Natural variations in coastal geometry can also help to amplify the magnitude of waves and tides as they reach the shore, providing natural concentration of a normally diffuse energy resource.

At first glance hydroelectric power would seem to have little relation to the Sun, but this appearance is deceiving. Hydroelectric dams work by exploiting the difference in gravitational potential energy between an upstream reservoir and its lower elevation outflow. Reservoirs require rivers to fill them, and rivers require precipitation in the form of either rain or snow. Precipitation originates from water vapor contained in the atmosphere, put there by evaporation of ocean water by the Sun. Hydroelectric, therefore, is just another way of collecting solar energy, which relies on natural river watersheds to focus the gravitational energy contained in continental precipitation.

Conclusions

It is often said that the three most important factors in real estate are location, location, and location. The same can be said of wind, rivers, waves, and tides as energy sources. Collectively they contain an enormous quantity of renewable energy, but most of this energy is spread too thinly across the enormous surface area of the Earth to be useful. For these energy sources to be practically exploited they must be naturally concentrated. Generally speaking this means that the availability of renewable energy from the fluid Earth depends directly on the geologic evolution of the solid Earth, which has shaped the world's coastlines, deserts, windy interiors, and mountainous river valleys.

Because of this requirement for natural geographic concentration, energy from the fluid Earth is not always found where we want it. For example, wind energy is abundant in North Dakota, where people are relatively scarce. In such cases the effective cost of renewable energy increases, because of the substantial infrastructure required to transport it where it is needed. In other cases the geography is more fortuitous; for example, much of the world's population lives near coastlines where wind, wave, or tidal power may be amply available.