Photo: Anders Karlqvist

Can Solar Energy Fuel the World?

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The primary motivation for developing renewable energy is to slow the accumulation of harmful greenhouse gases caused by combusting fossil fuels. A secondary motivation is to create a sustainable supply of energy for future societies. Though peak oil or peak gas is unlikely to occur soon, supplies of these are often unevenly distributed and at the whim of other nation states. In contrast, solar energy is plentiful enough everywhere, even in Northern Europe. Solar energy has developed rapidly in OECD countries as a significant component of electricity generation in the form of photovoltaics (PV), wind turbines, and biomass combustion. Complementary energy storage technologies have also rapidly expanded. An important question is whether these renewables, in particular low-cost solar photovoltaics, can provide a significant amount of world energy in the medium-term future (by 2050). In this essay, we highlight the advances of solar energy to produce liquid, fungible fuels.

The world used 162,000 TWh of energy in 2015 (1), which is three times more energy than it did in 1965. Estimates are that by 2050 the world's most populous countries will have slowed growth, and world energy usage will begin to level off at approximately 250,000 TWh (2). Approximately 80% of the energy generated today comes from fossil fuels, in the form of oil, coal, or natural gas. Solar photovoltaics supply a paltry 180 TWh (<0.1%,) and wind contributes 500 TWh. At a glance, it seems unlikely that solar photovoltaics could make a significant contribution. However, 81,000 TWh of energy hits the earth every hour and thus capture of 3 hours of sun exposure would satisfy the world's annual energy need in 2050. Put another way, the sunlight falling on the area of Portugal contains enough energy to meet all of world energy demand at any given time.

Solar panels to generate electricity

Although solar currently provides a small fraction of primary energy, the installed capacity worldwide has grown 20-30% per year since 1980, much faster than oil and gas did in their heyday, and the price per kWh has decreased nearly 50-fold. This growth rate has been remarkably consistent, and was seen in Germany from 1990 to 2010 and in China since 2011. As a result of this experience curve, solar energy is expected to reach price in parity with nuclear energy in 2020, and with coal by 2050 (3). If solar capacity continues to increase at a rate of 30% every year, it will reach 45,000 TWh by 2030 and could supply 20% of world primary energy and most of its electricity demand.

Solar panels based on biology

It is also possible to produce energy indirectly from sunlight, through microbial conversion of biomass. In the most common embodiments, biomass is cultivated, harvested, and gasified or fermented. This biomass can be food crops such as corn, rice, or wheat (1st generation), or non-edible cellulose (2nd generation). First-generation technologies are widespread: bioethanol produced by yeast fermentation of grain or cornstarch accounts for 10% of all motorcar fuels in the US and China. However, there is little room to expand first-generation technologies. Nearly 50% of the US corn crop is already dedicated to ethanol (4).

Second-generation technologies focus on the use of non-edible crops or waste biomass. Anaerobic digestion of biomass using a mixture of microbes typically produces methane, which can be used directly in some cars and trucks or converted to liquid fuels. Thermal gasification of biomass yields synthesis gas, a mixture of CO, CO_2, and H_2 that can also be catalytically or biologically upgraded to methane or other motor fuels. In Sweden, GoBiGas (Göteborg Energi) collects waste biomass for thermal gasification to synthesis gas, which is then catalytically upgraded to methane. A similar project was initiated by Chemrec to produce synthesis gas from paper-mill waste streams and catalytically upgrade it to methanol and dimethyl-ether (DME). A facility in Piteå was operational for several years and the fuels were successfully used in Volvo trucks. However, these projects suffer from challenging economics.

Overall, the solar-to-fuel efficiencies of first and second-generation biofuel processes are low (< 0.5%) because they require a biomass intermediate (Figure 1) (5). Plants typically convert solar energy to biomass at efficiencies of 1%. This is because half of the solar spectrum is not photosynthetically active and a significant amount of the energy that is captured is lost converting CO_2 to biomass. After harvest, energy is lost as heat during processing and fermentation. Additional losses are incurred if upgrading synthesis gas to usable fuels. As a result of compounding these inefficiencies, large areas are required for crop planting or to collect agricultural waste to produce significant amounts of fuel, and net energy ratios can be low (1.5 for corn ethanol, 3.5 for cellulosic ethanol (6).

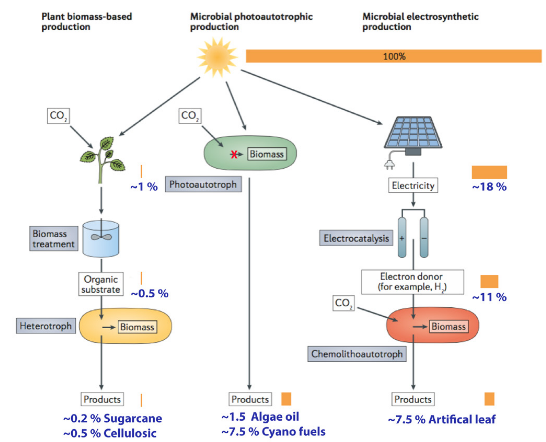

Figure 1. *The conversion of solar energy to liquid fuels is a field of active research. Left: In 1st and 2nd-generation processes, biomass is harvested and either fermented to produce liquid biofuels or combusted to produce gas, which can then be upgraded to fuels. These have low overall efficiencies. Middle: In a direct solar fuel process, CO_2 is converted to products inside a photosynthetic cell using light energy. The cell does not accumulate biomass, so that more captured energy can be diverted to product. The increase in efficiency is considerable. Right: In a PV-biological system, solar-generated electricity is used to power H_2 formation, which is then fed to bacteria as energy for capturing CO_2 and converting it to fuels. Due to the high efficiency of solar panels and electrochemical processes, the PV-biological system could have high overall efficiency. Note: This figure is adapted from (Claassens et al, 2016) and edited to include data for a cyanobacteria-based process.*

It is possible to improve biofuel production efficiency through genetic engineering of the microbes that metabolize cellulose. Adding new metabolic pathways can provide significant increases in conversion yields. New types of yeast and other bacteria strains are now being implemented for direct biological conversion of cellulose waste and synthesis gas to automobile fuels such as ethanol and butanol. The demonstrated yields from these new strains are 50% higher than previously possible (LanzaTech, USA; White Dog Labs, USA). Importantly, these fuels are being upgraded to energy-dense aviation fuel ("Alcohol to Jet," Swedish Biofuels AB), providing a non-petroleum source of fuel for that market, though the cost is currently prohibitive. While these technologies are improving, it is unlikely that conversion of biomass to liquid fuels can sustainably meet our liquid fuel needs (7), and they are thus unlikely to gain a market share larger than that currently held by bioethanol.

Some of the drawbacks and inefficiencies in biomass conversion processes for liquid fuels can be overcome by direct solar-to-fuel conversions, in which there is no accumulation or harvesting of a biomass intermediate (Figure 1). These can be fully biological or PV-biological hybrids. In one promising example, photosynthetic bacteria such as cyanobacteria are genetically engineered to produce and secrete ethanol (Joule Unlimited, USA)(8); (Algenol, Germany). The bacteria are designed to divert very little of captured CO_2 and light energy to biomass nearly all of it to fuel product. In these systems, solar-to-fuel efficiencies are 7.5%, more than half of the theoretical limit (9). Start-up companies operating in the US and Europe have built pilot-scale or demonstration-scale facilities to grow these bacteria in clear, enclosed plastic reactors. Importantly, these direct solar-to-fuel facilities do not use fresh water and are located in areas where there is no agriculture. Furthermore, the bacteria are not for human consumption and are not fit enough to survive outside of the enclosed reactors. However, these facilities do require large areas, since the light-absorbing surfaces must be large. This typically translates to higher process energy inputs for culture mixing and fuel separation. In spite of this, the resultant fuel is nearly cost-competitive with petroleum and has a GHG footprint that is 85% smaller than petroleum (Joule Unlimited SunFlow). Basic research is ongoing to further improve the efficiency of these solar fuel processes. One goal is successful integration of light-sensitive proteins that are responsive to 700 nm-900 nm, which would extend the spectrum available to photosynthesis to be similar to photovoltaic panels (10).

In an alternative, PV-biological process, solar panels are coupled to electrodes that use electric current to produce hydrogen (Figure 1). The hydrogen is stored and can be fed, along with CO_2, to genetically engineered bacteria. The bacteria use the hydrogen to upgrade the CO_2 into an energy-dense liquid fuel. This hybrid process benefits from the efficiencies of solar panels (10-20%) and electrochemical conversion of water to H_2 (50%). Finally, the genetically engineered microbes can use the H_2 energy to produce liquid fuel at 40-50% efficiency. Overall, commercial solar-to-fuel efficiency can be approximately 5%, though this is expected to increase as solar panel efficiency rises. One benefit of these systems over biological photosynthetic systems is that less water and less area is needed. Integrated PV-biological systems are currently being tested at laboratory stage, and a recent prototype called the "Artificial leaf" reached 7.5% solar-to-fuel efficiency (11). Large-scale deployment of this technology would require a significant expansion of the industrial electrolyzer, as most hydrogen is currently produced from natural gas (12).

Conclusions

Here we discuss the dramatic development of the technology behind the use of solar energy to fuel the world. The combination of solar voltaics and biological alternatives has the potential to provide a sustainable resource of energy based on both electricity and liquid fuel. It is very likely that solar voltaics will contribute a majority of worldwide electricity by 2050. The rapid capacity expansion and decline in cost in the past 20 years has been unprecedented, rivaled only by perhaps DNA sequencing technology in the life-science sector. A similar, though not as extreme, experience curve is occurring for lithium-ion batteries, so that these may be the primary solution to the intermittency problem. In the transport sector, it is likely that fully electric or fuel cell-powered automobiles will have a significant market share by 2030. A promising alternative to the solar voltaics is direct solar-to-fuel process using photosynthetic bacteria and hybrid PV-biological systems using electrolysis-generated hydrogen. In both cases, the technology in these cases are far from commercially attractive and more basic research is needed to increase solar capture efficiency and metabolic conversion of CO_2 to liquid fuel.

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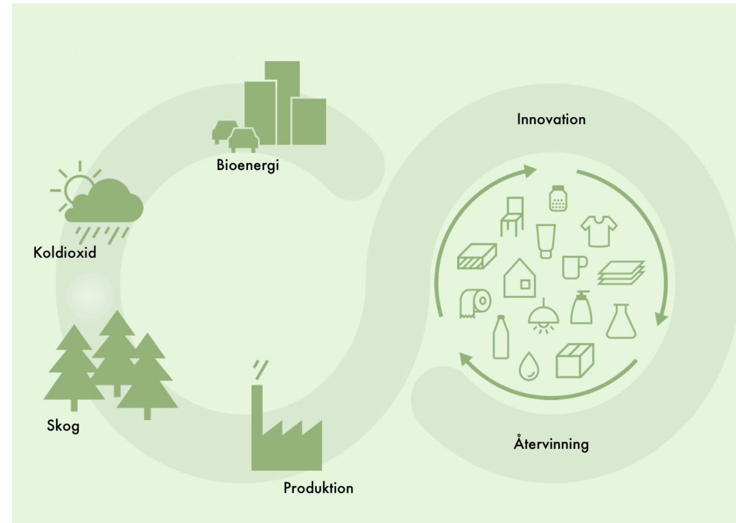

Diagram: Creuna

Forestry: A Key to Sustainable Development

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The Royal Colloquium 2016 focused on opportunities and concrete solutions for sustainable development, and was thus an excellent forum for highlighting the role of forests in this process.

There are many ways in which sustainably managed forests and their products help mitigate climate change and contribute to sustainable development:

• Through photosynthesis, growing forests absorb large quantities of carbon dioxide and thus combat the greenhouse effect.

• Forests produce renewable raw materials that can replace their fossil equivalents.

• Everything made with oil can be made with wood.