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. 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 trends in cost and market penetration of solar photovoltaics. We also discuss limitations in the advance of solar energy, as well as ways that solar energy is used to produce liquid, fungible fuels. We note that wind energy is also rapidly increasing its market share, though not as quickly as photovoltaics.

The world used 162,000 TWh of energy in 2015 (International Energy Association, 2015), 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 (BP Energy Outlook, 2016). 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%,) 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 3 hours of sun exposure would satisfy the world's energy need for 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 **(Figure 1).** For a more local comparison, the island of Corsica receives enough energy from sunlight to power all of Europe and Russia.

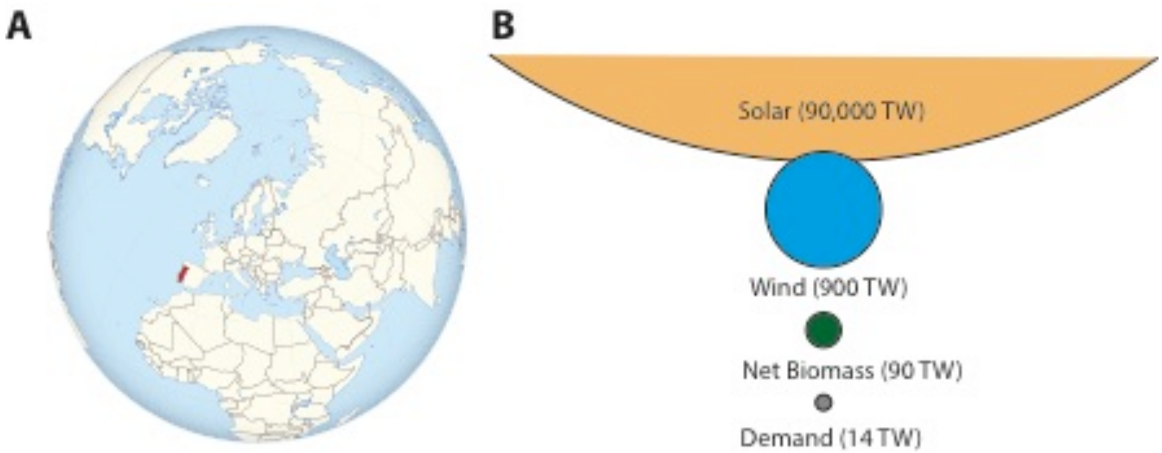


Figure 1. The solar energy of the world. A*. Enough sunlight falls on the area of Portugal (in red) during the year to meet the world's energy demand, 162,000 TWh* ***B.*** *The accumulated power available in sunlight, wind energy, and net biomass per year. Each of these is more than enough to meet our current and future energy demands.*

Solar power is coming of age

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 **(Figure 2)**. This growth rate has been remarkably consistent, and was seen in Germany from 1990 to 2010 and has been occurring in China since 2011.

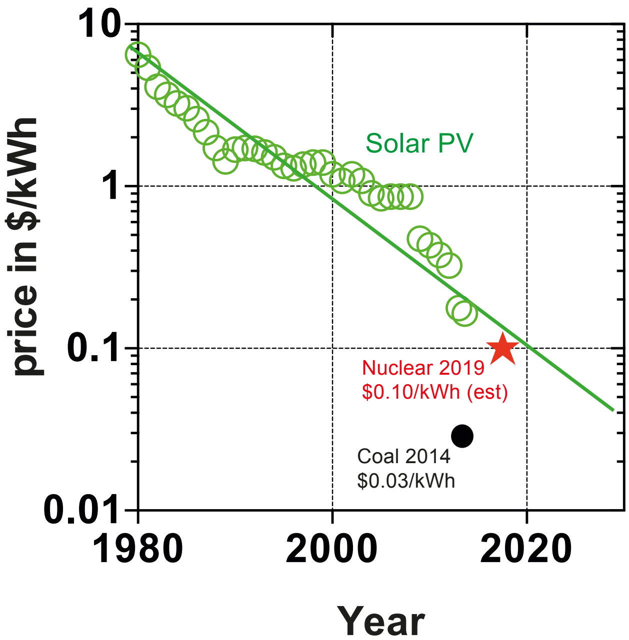


***Figure 2*. The dramatic decrease in the cost of solar panels is shown**. *Costs per installed capacity (Watt) have been converted to an estimated leveraged cost per energy ($/kWh) as described by Farmer and Lafond, 2016. Solar energy is expected to be cheaper than nuclear energy by 2020 and cheaper than coal energy by 2040. Note: This figure is re-made based on data from Farmer and Lafond (2016).*

As a result of this experience curve, solar energy is expected to reach price parity with nuclear energy in 2020, and with coal by 2050**.** If solar capacity continues to increase at a rate of 30% every year, it will reach 45,000 TWh by 2030, which would be approximately 20% of world primary energy supply and most of estimated electricity demand **(Figure 3)**. Worldwide, solar photovoltaics are already 50% of all new energy capacity installed. This simple extrapolation differs from estimates given by BP's annual energy outlook for 2016, that predicts solar power will be 7-8% of electricity generation in 2035. Considering solar-to-electricity efficiencies are 10% for commercial silicon-based solar panels (Kumar et al, 2009), a 45,000 TWh market penetration of photovoltaics will likely require dedicated solar fields, more than just a solar panel on every roof. A rough calculation is that covering roofs in an OECD country such as Germany with solar panels could supply 20% of that country's electricity demand. However, this value will improve, as breakthroughs in solar efficiencies occur steadily. The latest laboratory-scale silicon panels perform at 24% solar-to-electricity efficiency (Panasonic corp., 2016).

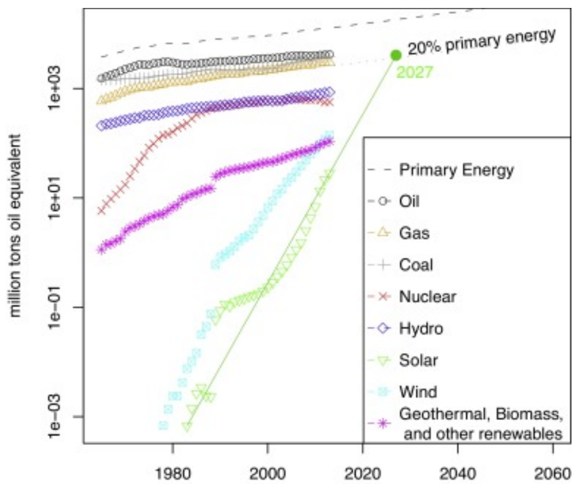
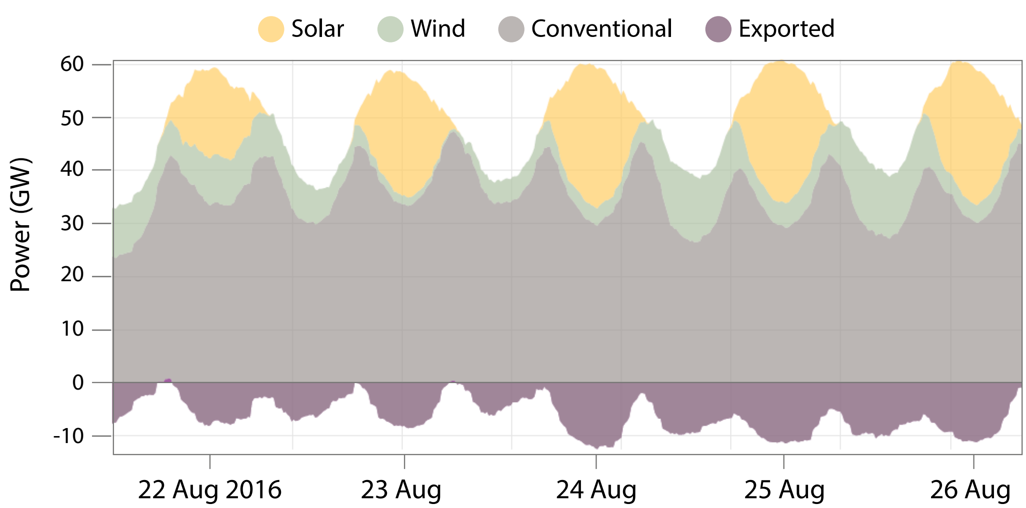


Figure 3. The wind and solar power have grown rapidly in the energy market since 1980. *Currently, solar power accounts for less than 0.1% or world generation. However, following current trends, solar could provide 20% of total energy by 2030. Note: This figure is taken from Farmer and Lafond 2016.*

When the sun doesn't shine

The biggest obstacle for solar photovoltaics gaining market share is intermittency of the source. Solar panels are typically assumed to operate 6-8 hours per day, and have significant variations within the day. The generated power can be 10-times higher in July than in December, while load (demand) remains relatively stable (Hoppman et al, 2014). Similar problems plague wind power. Current energy grids do not have an economical way to store solar or wind power for later use. As a result of intermittency, conventional power sources must be at the ready for when solar and wind power drops. The intermittency problem is solved relatively easily in Sweden due to an abundance of hydroelectric power; hydroelectric dams are typically load following and can adjust their output to accommodate an increase of solar energy to the grid. Gas turbines are also relatively flexible. In contrast, power plants that run on coal, nuclear, and biomass are generally base-load, meaning that it is difficult and uneconomic to turn them off and on. As a result, solar and wind energy are often only supplements to conventional power.

Recent energy data from Germany highlights the severity of the intermittency problem. Combined wind and solar have grown rapidly in Germany from 2008 to 2016. On some summer days, solar and wind can meet 80% of total electricity demand (MIT Technology Review, 2016). However, because coal-fired power plants must be kept on as base-suppliers to combat intermittency, CO_2 emissions in Germany have not significantly dropped since 2008 (Eurostat, 2016). Instead, during high-sun or high-wind, coal-generated electricity is exported abroad (Figure 4). A similar scenario is playing out in the southwestern United States. Since coal-fired plants currently provide 40% electricity production worldwide, it is reasonable to assume that these will remain as base-load providers as solar and wind expand. The most attractive solution to this problem is to develop novel energy *storage* solutions. Only then will the transition to a fully renewables portfolio succeed in combating GHG emissions.



Net generation of power plants for public suppy in Germany wk 34 2016
Adapted from Fraunhofer ISE Energy Charts

Figure 4. Electricity generation in Germany during one week of August 2016*.* *Shows the power generated by solar, wind, or conventional sources (coal, natural gas, and nuclear). Note that in times of intense solar or wind supply, electricity is exported. This is because conventional power sources cannot be easily shut down when not*

needed. Note: This figure is a snapshot taken from Fraunhofer ISE website and edited to enlarge scale bars.

Batteries for short-term storage

An obvious technology for short-term electricity storage is batteries, such as the pervasive lithium ion types. Due to the proliferation of electronic devices, and now electric cars, lithium-ion batteries are also on an experience curve. Recent projections from the Stockholm Environment Institute are that lithium ion battery packs for automobiles are decreasing in cost at 14% per year and that costs could be $150/kWh by 2030 (Nykvist and Nilsson, 2015). An automobile battery pack of 20 kWh would thus cost $3000 and last 5000 cycles. These types of packs would be more than enough for home use, as the daily residential electricity consumption Sweden is 15 kWh per capita (Swedish Energy Agency, 2015). Companies such as Tesla (US), Mercedes (GER), and Enphase (US) are already producing lithium ion battery “Powerpacks” for residential (6.5 kWh) and commercial (100 kWh) storage and distribution of electricity. A recent survey found that such residential PV-battery storage combination could already be economically viable in Germany, since currently excess power is sold to the grid at low cost, and bought back at high cost at night (Hoppman et al, 2014).

Industrial-scale (>5 MW capacity) battery storage is also being deployed and tested for both quick, high-power delivery and longer, low-power delivery. For example, in 2014 Southern California Edison contracted with LG Chem to build a battery bank capable of producing 8 MW for 4 hours (32 MWh storage), which is one of the largest battery bank in the world, equivalent to 1,000 electric car battery packs. The batteries store energy from 5,000 wind turbines (Greentech Media, 2014). On Kauai, Hawaii, a single 13 MW solar farm consisting of 60,000 solar panels produces 20% of the islands electricity (pop. 60,000). The farm is coupled to a 6 MW capacity lithium ion battery array that stores excess electricity during the day and re-supplies it during cloud cover and at night. Dozens of industrial PV-battery systems are under construction in the US, Europe, and Asia (US Department of Energy, 2016). Such PV-battery systems are particularly attractive for remote locales as they can *potentially* eliminate the need for a base-load power provider.

However, one *potential* problem for the widespread use of lithium ion batteries is the supply of lithium. Worldwide lithium reserves are estimated at 14 Mt (US Geological Survey, 2016). The average battery pack for an electric car contains 1 kg of lithium. Full electrification of >1 billion cars and >1 billion homes would thus require 2 Mt of lithium, a substantial amount of total reserves. Worldwide production was 32,000 t in 2015, so it lithium extraction will need to increase considerably to meet this demand.

Biomass as long-term storage

The primary energy storage mechanism on the planet is biomass, as the biological reactions of photosynthesis capture solar energy and store it as sugars. Of the 90,000 TW of solar energy that hits the planet each year, terrestrial and aquatic plants and algae store approximately 30 TW and 60 TW, respectively (Ringsmuth et al 2016). This natural primary productivity (NPP) is significantly more than the world energy demand and at first glance appears to be an easy way to meet our energy needs. In fact, biomass thermal conversion such as combined heat and power or gasification, and chemical conversion such as anaerobic digestion to methane provide 5-10% of electricity generation in many EU countries (European Commission, 2014).

However, a key constraint on the use of biomass to meet energy demands is that it should not interfere with food production or impact ecological systems. Though humans consume just a small fraction of yearly NPP as calories, it has been estimated that 25-50% of terrestrial NPP is already used indirectly for food and energy (Erb et al, 2009). Therefore, it is unlikely that biomass can *sustainably* contribute more to growing energy demands in developed countries. However, small-scale biomass harvesting could be implemented in sparsely populated, developing countries that currently do not have extensive energy grids. For example, a biogas-burning plant could supplement solar electricity in a small village.

How can solar power change the transportation sector?

So far we have considered how solar energy could penetrate the electricity market, particularly when combined with batteries for storage. What about the transport sector? Transport accounts for 30% of worldwide energy usage and >50 % of world oil usage **(Figure 5),** and demand for oil is expected to increase 30% by 2040 due to increases in car ownership in China and India (BP Energy Outlook, 2016).

The most direct way to utilize solar power in the transportation sector is in an electric vehicle, where the battery is charged using solar power. Currently, electric cars constitute 1% of new car sales worldwide, but are increasing so rapidly that they are expected to be 35% of all new cars sold worldwide in 2040 (Bloomberg New Energy Finance, 2016). This portends an eventual shift in automobile transportation toward electricity, and thus, indirectly solar-powered. However, it will take several decades to phase out gasoline-powered automobiles. Therefore it is expected that in 2050 oil will still be the dominant currency in automobile transportation.

While electric cars may steadily gain market share, progress in electric aircraft has been significantly slower. Air travel accounts for 11% of petroleum usage, is growing at 4% annually, and is expected to double by 2035, with strong growth in China and India (Intl Aviation Transport Administration, 2015). Though there is intense research in developing lighter electric drives for airplanes, the current state of the art is the 2-seater electric Airbus E-Fan, which has a 1-hour flight limit. The biggest obstacle for the development of electric planes is the low energy density of batteries; which are at least 45 times heavier than oil on a per-energy basis. Therefore, we expect that liquid fuels will be necessary for aviation transportation for the foreseeable future.

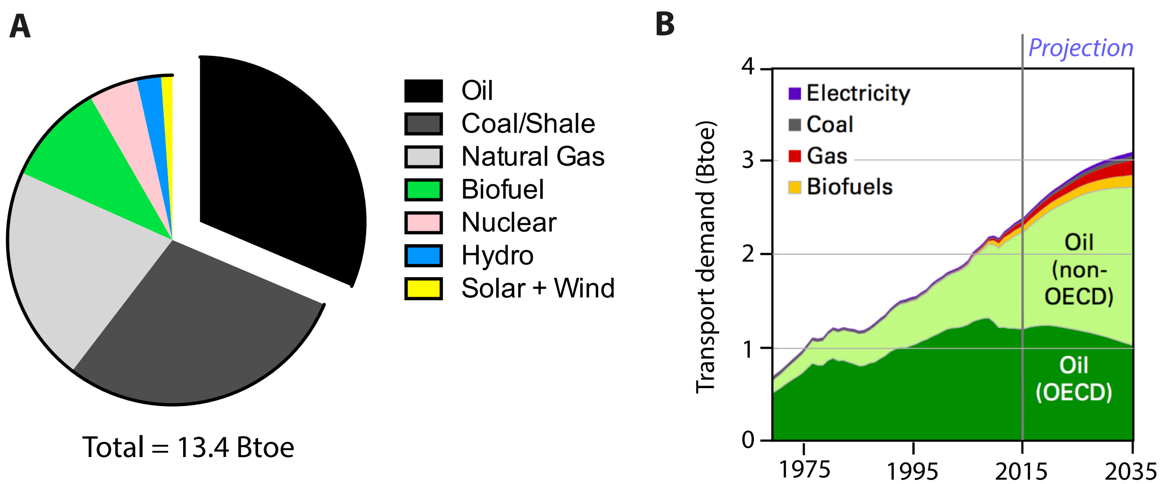


***Figure 5.* Energy for transportation**. *A: **World energy supply divided by sources (2012).** Approximately 30% of energy is supplied as oil. The majority of this oil is used in transport (Energy Information Agency, 2012) B: Estimates for world transport energy usage out to 2035 show that demand for oil will continue to grow. Note: Figure 5B is taken from the BP Energy Outlook 2016 and adapted to enlarge axes.*

It is of course possible to produce transportation fuels indirectly from sunlight, through chemical or 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. In general, there is little room to expand first-generation technologies. Nearly 50% of the US corn crop is already dedicated to ethanol (US Department of Agriculture, 2016).

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, neither of these projects are likely to be expanded due to poor 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 6;** Claassens et al, 2016). 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 combustion or 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; Schmer et al, 2008).

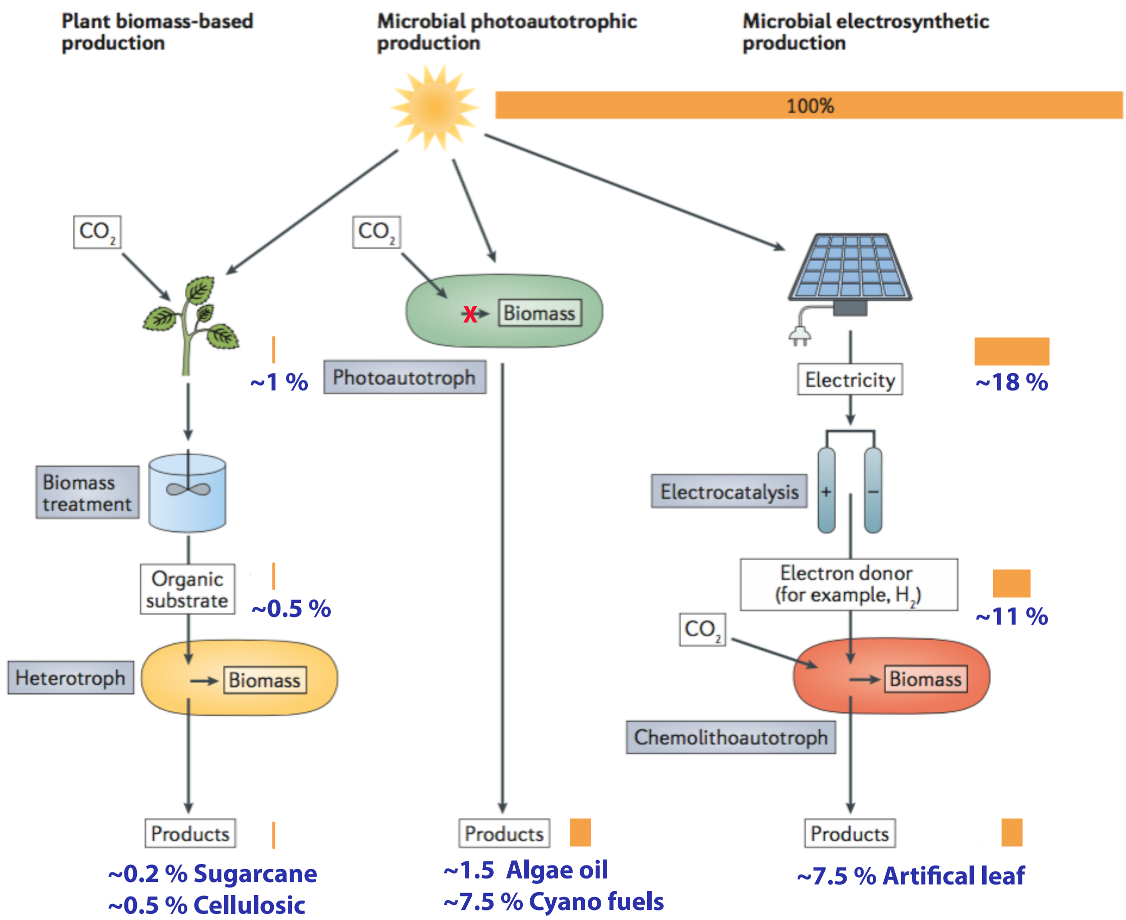


Figure 6. **The conversion of solar energy to liquid fuels is a field of active research.** ***Left:*** *In 1st and 2nd-generation processes, biomass is harvested and either fermented to produce liquid biofuels or combusted to produce gas, which can then be upgraded to fuels. These have low overall efficiencies.* ***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 taken from Claassens et al Nature Reviews Microbiol 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 significantly increases in conversion yields. New types of yeast and other bacteria strains are being 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 (Erb et al, 2009), and they are thus unlikely to gain 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 6, middle and right)**. 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; 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%, which more than half of the theoretical limit (Robertson et al, 2011). 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 (Blankenship et al, Science 2011).

In an alternative, PV-biological process, solar panels are coupled to electrodes that use electric current to produce hydrogen **(Figure 6)**. 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 (Harvard Gazette, 2016). Large-scale deployment of this technology would require a significant expansion of the industrial electrolyzer, as most hydrogen is currently produced from natural gas (Bertuccioli et al, 2014).

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 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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