Artificial Photosynthesis for Solar Energy Storage: Toward a Sustainable and Equitable Future

Christina Chang and Rebecca Farnum

It has never been more urgent for us to go green. The Intergovernmental Panel on Climate Change has just released its latest report [1], the headline: if our emissions continue, the worst is yet to come. It is widely accepted that we must reduce our reliance on fossil fuels – if not for the sake of our environment then to help insulate our energy supply stream from volatile fossil fuel markets, which are becoming more uncertain as reserves are depleted [2, 3]. In December 2008 the European Council took a monumental step in the right direction by setting legally binding targets for the year 2020, among them a 20% reduction in greenhouse gas emissions [4]. Half of the timeline's twelve years have passed and our renewables uptake is on track: renewables comprised 14.1% of all European energy usage in 2012, up from 10.5% in 2008 [5, 6]. We are about halfway there.

One could argue that deploying renewable energy technologies will get easier from here on out; after all, solar panels and wind turbines will become cheaper as they are more widely produced, benefitting from economies of scale. However, when we try to increase the share of renewables, thereby decreasing dependence on conventional energy sources, a particularly insidious problem arises. Something important differentiates renewables from fossil fuels: fossil fuels are dispatchable (you can reliably burn them at any time you like), but most renewables are intermittent (the wind doesn't blow all the time, and solar panels are useless at night and pitiful under rainy or cloudy conditions).

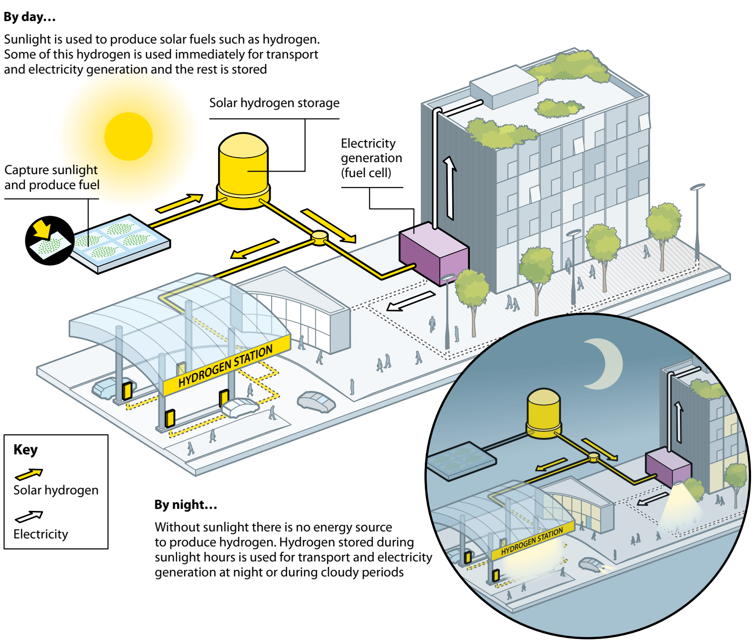
If we require our energy to be reliable, then a wind farm isn't "worth" as much as a coal plant—this worth is termed "capacity credit". From the perspective of statistical reliability, energy from wind is currently worth about 30% of energy from fossil fuels – that is, for every 1,000 MW coal plant we shut down, we would need to set up about 3,300 MW of wind farms in order to guarantee that the lights stay on all the time [7]. Unfortunately, this ratio decreases exponentially the more we decrease the fossil fuel share. That is the fundamental problem. For a hypothetical electrical grid, to shut down the next 1,000 MW coal plant, we would need 4,000 MW more peak wind capacity (now wind has a capacity credit of only 25%). The same argument applies for solar panels, another intermittent energy technology. Because of these diminishing capacity credits, the deployment of renewables yields exponentially less gain.

To solve this problem and enable the further deployment of renewables, we will need to store the renewable energy – that is, we will need technologies that transform our renewable power into something more like our current, dispatchable fossil fuels. Dispatchable renewable energy would have a capacity credit of 100% and therefore make our 2020 and future targets much easier to meet. There are many sustainable technologies being tested for their ability to provide grid-scale energy storage. Biofuels, novel batteries, pumped hydro and molten salt solar concentrators are all on the horizon. This article aims to highlight an exciting, emerging technology for energy storage called artificial photosynthesis (solar fuel production).

By developing artificial photosynthesis, scientists are taking a leaf out of nature's book. Green plants have developed a process that absorbs energy from sunlight and transfers it into a chemical bond, turning carbon dioxide and water into sugar (the energy storage or 'fuel') and oxygen (a byproduct). The natural process of photosynthesis is safe and scalable, and provides a model for generating renewable, storable energy. In the lab, scientists are attempting to mimic this natural technology [8]. They seek to develop a device that absorbs energy from sunlight, exactly like plants do, and transfers it into a chemical bond, transforming carbon dioxide and/or water into fuels (e.g. hydrogen or methane). In this process, the solar energy is transferred to the fuels, which can be stored indefinitely. In this way, an artificial photosynthesis device – aptly nicknamed an "artificial leaf" – will be able to store solar energy in the form of fuels, making it a 'solar-charged battery' [9].

The first practical artificial leaf prototypes, developed in the past few years, produce the simple fuel hydrogen gas (H_2) by using sunlight to split water (H_2O) into hydrogen (H_2) and oxygen (O_2). The "hydrogen economy" concept

Solar energy around the clock



works toward a carbon-free hydrogen fuel that can be used in a fuel cell, an electrochemical engine that is inherently more efficient than the internal combustion engines we use with fossil fuels [10].

Currently, mainstream electricity is generated at large power plants, relying on a grid to transport the energy. In contrast, artificial leaves, when fully implemented, will be able to produce, store, and supply fuel locally, meaning they can be used regardless of surrounding infrastructure [11]. Artificial leaves could thus help address the needs of rural and remote communities currently off the grid, households requiring back-up emergency power sources for electricity-dependent medical devices and temporary shelters for refugees or even recreational campers.

Sustainable energy is becoming increasingly common, from wind farms and hybrid vehicles to solar panels on buildings [12]. However, these environmentally friendly sources continue to be primarily the domain of the privileged. Sustainable energy technologies are often cost prohibitive and/or entail too many infrastructure barriers to be accessible to those in developing countries [13]. Unfortunately, those who are most vulnerable to the impacts of climate change are also those who have the least capacity to help mitigate it or benefit from the technological advances we have made [14].Artificial photosynthesis provides a conceivable solution to not only our needs for storable renewable energy, but also the issue of energy justice. Artificial leaves provide a potential mechanism for the democratisation of energy-dependent technologies, furthering global access to transportation, home electricity and backup supplies. Artificial leaves that store fuel on-site could obviate the prohibitively capital-intensive electricity grid infrastructure preventing some other renewables from reaching rural and underserved populations. The local production and storage of solar energy would mean that more people around the world could have regular access to electricity, which would profoundly improve health prospects and lifestyles. Moreover, an abundant energy source that does not release CO_2 and other greenhouse gases would give developing countries and communities an avenue for economic development that does not further exacerbate climate change.

It is an enormous technological challenge to create an artificial leaf that is both scalable and economically feasible. The issues of accessibility and affordability for the developing world should be considered now at the research stage. Although scientists have made considerable progress in this field, policymakers must also now do their part by investing public resources in artificial photosynthesis research and by considering societal mechanisms for the uptake, dissemination, and accessibility of these technologies. Doing so, they can help shape the content and direction of the work. Some governments have already set clear targets for artificial photosynthesis technologies [15]. Expanding this attention and increasing dialogue between scientists and policymakers could help facilitate artificial leaves to grow to their full potential of helping to solve our energy needs, reducing our negative impacts on the planet, and providing accessible sources of electricity for the most vulnerable.

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About the Authors

Christina Chang is a 2012 Marshall Scholar pursuing an MPhil in Chemistry at the University of Cambridge, where she conducts research on artificial photosynthesis in the laboratory of Dr. Erwin Reisner. She holds an MSc in Sustainable Energy Futures from Imperial College London and a bachelor’s degree in Chemistry from Princeton University. Outside of the lab, Christina is passionate about furthering science education.

Rebecca Farnum is a 2012 Marshall Scholar pursuing an LLM in International Law focused on environmental and human rights law at the University of Edinburgh. She holds an MSc in Water Security and International Development from the University of East Anglia and bachelor’s degrees in anthropology, interdisciplinary humanities, international development, and international relations from Michigan State University.