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Hen Dotan, Hatmut Michel, Steven Chu, Stafford Sheehan and Heather Mayes debate the pros and cons of biofuels and solar electricity for Nature Video.

ENERGY

Fuelling the future

Are biofuels the way forward, or should we be looking to advanced solar technologies to power the future? The debate began on Lindau and continues here.

Making liquid biofuel from plant materials is a controversial approach to securing our energy future. At the Lindau Meeting of Nobel Laureates, two laureates and three young researchers debated the science behind biofuels for Nature Video, and they carry on the debate in these pages.

Heather Mayes: The primary message from the biofuels debate is Steven Chu's optimism that our future will be powered by renewable energy, and that biofuels will make a valuable contribution to that future.

In discussing renewable energy options, it is essential to consider the whole process: the resources required, the amount of useful energy created, and requirements for scientific advances or new infrastructure. If we focus too narrowly on one aspect of a technology, we will miss its full promise (and peril). In discussing biofuels, Hartmut Michel concentrated on the fact that plants capture only a small percentage of sunlight, but we do not need to absorb all of the solar energy that reaches the earth — that would vastly exceed humanity's energy needs. It is more important to avoid interfering with the food supply — a problem with maize-derived ethanol that might be overcome by producing biofuels from agricultural and forest wastes instead.

Another issue is the expense and difficulty of transporting bulky biomass and converting it to fuel. The costs of converting biomass waste to fuel have decreased by more than two-thirds since 2001 (refs 1, 2), and transport difficulties can be reduced by building biorefineries near agricultural centres. If these issues can be overcome, biofuels will fill a demand not met by other sources of renewable energy: a liquid fuel that can be distributed through our current infrastructure. Biofuels are also the only alternative to fossil fuels that can provide sufficient energy density for industries such as air travel. With non-food biofuels on the cusp of becoming more affordable and available, we should not turn our back on this promising technology.

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Stafford Sheehan: As Chu pointed out, from the fuel consumers' point of view, the most important factor is the price at the pump — this will determine whether a renewable fuel will be widely used, but it is not the only consideration. One issue that was overlooked in this debate is that people prefer the path of least resistance, and thus will favour the easiest way to convert and store energy. Agriculture has been a part of human culture for millennia — we know how to grow plants. But biofuels have drawbacks: for example, they can be produced only in regions with plenty of arable land and ample food supplies. In addition, the yearly solar conversion efficiency of crop plants averages less than 1% (although this varies over the course of the growth cycle)[3]. The low rate of production of biofuels and their geographic dependence are not sustainable, especially given our planet's growing population.

Commercial photovoltaic cells convert energy more effectively than biofuel crops, and Michel proposed them as a solution to our energy needs[4]. However, this technology is not suitable for all applications, or appropriate for all parts of the world. A major problem is the lack of a good way to store the energy with a density approaching that of gasoline. In the long term, we need to invest in artificial photosynthesis — the conversion of sunlight to chemical energy, stored in molecular bonds within a fuel. Artificial photosynthesis requires less land than biofuel crops and has a higher production rate, so it will probably be our primary source of renewable fuel in the future.

Hen Dotan: Throughout the debate, Chu emphasized the cost of alternative fuels. But how do you know the cost of an emerging new technology? For example, when silicon photovoltaic cells were first produced in 1954 they were very expensive (US$1,785 per watt) and inefficient (about 6% in the lab, but 2% for commercial products). But, with government subsidies and time, the price of these cells dropped to just $0.78 per watt in 2012, with their efficiency surpassing 25%.

Michel argued that biofuel research should be abandoned because photosynthesis is inefficient and energy crops compete with food crops for limited resources such as fresh water, arable land and fertilizer. I agree and I think that artificial photosynthesis is a better way forward; as in natural photosynthesis, the first step is to split water into oxygen and hydrogen using solar radiation. The hydrogen can be used directly as fuel or combined with carbon dioxide to produce methanol or other hydrocarbon fuels. This process has a theoretical efficiency of more than 15% — significantly higher than natural photosynthesis. In the last year, solar-to-hydrogen conversion efficiency has reached almost 5% using a cheap iron-oxide-based photo-anode[5]. Artificial photosynthesis devices are already mature enough to be implemented in remote locations where it is difficult to supply conventional fuels. Further progress, stimulated by government subsidies, could make this technology competitive with fossil fuels within ten years.

Mayes: We would all love to have a renewable energy technology that is inexpensive, works everywhere and has no drawbacks. Unfortunately, contrary to what Dotan is saying, none exists; if it did, fossil fuels would be a distant memory. There are drawbacks to each renewable energy technology. Fortunately, we do not need one technology to solve all our energy needs; we can use many, choosing the most appropriate for each situation.

I disagree that we should abandon research into biofuels. Next-generation biofuels that use biomass or waste, and don't interfere with our food supply, are almost here. Additional investment in biofuel technology will help to drive costs lower. To continue tackling the difficult problem of climate change, we should invest both in a wide range of near-term, near-market technologies, such as biofuels, and in basic science research, which will lead to unforeseen technologies.

Sheehan: Dotan is being optimistic: science may be able to find a solution, but if the basic idea is not cost effective a technology will never be widespread regardless of how much production is optimized. New technology has to take into account the abundance of the resources it uses. For example, silicon solar cells use the second most abundant element in the Earth's crust. It's doubtful that solar cells would be as widespread as they are today if they relied on rarer elements such as gallium or indium.

> ***"New technology has to take into account the abundance of the resources it uses."***

Now look at the technology for splitting water into oxygen and hydrogen. An ideal water-splitting cell is made using rare earth elements, which are expensive and scarce. Fifteen years ago, such systems achieved efficiencies of 12.4% (ref. 6), but research switched to technology that uses more abundant compounds such as iron oxide[7]. Even using abundant elements, however, the estimated cost of hydrogen produced by the 'artificial leaf' is around US$6.50/kg; hydrogen produced by steam reforming of hydrocarbons costs less than $2.00/kg (ref. 8). While I agree that artificial photosynthesis will be our long-term energy provider, this technology is not ready. Plenty of basic research needs to be done first. Until then, biofuels remain a viable fuel option.

Dotan: While I agree with Sheehan that price is an important factor for consumers, I would add that many people are bad at understanding long-term costs. For example, consumers still buy cheaper incandescent light bulbs, even though switching to energy efficient light bulbs can lower their total domestic electricity consumption by as much as 10%. Such is this disparity in short-term versus long-term cost that governments around the world are starting to ban incandescent light bulbs. This is an example of a free market failure, and I fear that biofuels could well become a second example — that is, that their short-term appeal will outweigh their long-term problems in the eyes of consumers.

Biofuels possess two major drawbacks. First, as noted, their production is inefficient. Second, biofuels still lead to polluting vehicle exhaust emissions. Depending on fuel type, these emissions might be lower than for conventional fossil fuels (although the evidence is currently inconclusive) but they are not pollution-free. I believe that artificial photosynthesis is already more efficient than biofuels and this process produces hydrogen, which is truly a zero-emission fuel (the only byproduct of burning hydrogen is water). Unfortunately, without proper regulation of biofuels and proper support for artificial photosynthesis, I worry that fossil fuels will be replaced by inefficient and polluting biofuels despite there being a better alternative. Even if global regulations limit biofuel feedstock to agricultural and forest wastes, as suggested by Mayes, we must focus on artificial photosynthesis research and implementation to ensure sustainable fuel production. ■

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LAUREATES

Steven Chu was co-awarded the Nobel Prize in Physics in 1997 for his work developing methods to cool and trap atoms using lasers. He served as the US Department of Energy secretary from 2009 to 2013, and has since returned to Stanford University in California.

Hartmut Michel was co-awarded the Nobel Prize in Chemistry in 1988 for elucidating the action of membrane-bound protein in photosynthesis. He is based at the Max Planck Institute of Biophysics in Frankfurt, Germany.

RESEARCHERS

Hen Dotan is a PhD candidate at the Department of Materials Science and Engineering of the Technion – Israel Institute of Technology in Haifa. His research is on solar hydrogen production by photoelectrochemical water splitting.

Heather B. Mayes is a PhD candidate in the Department of Chemical and Biological Engineering at Northwestern University in Evanston, Illinois. She is studying the molecular reactions that can convert non-food biomass into renewable energy and chemicals.

Stafford W. Sheehan is a graduate research fellow in the physical chemistry PhD programme at Yale University in New Haven, Connecticut. His research explores materials science, catalysis and artificial photosynthesis.