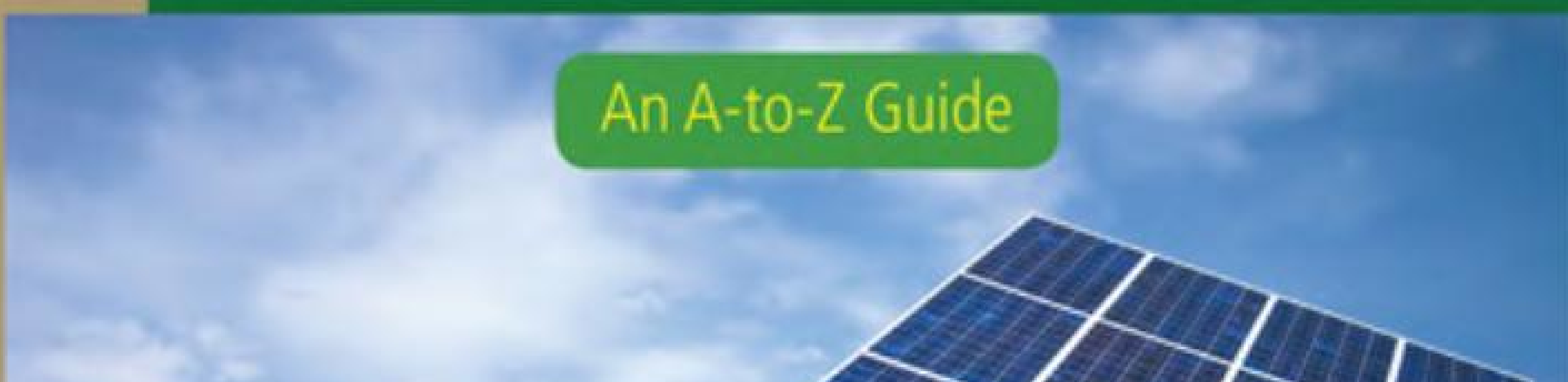
The SAGE Reference Series on
Green Society
Toward a Sustainable Future

Green Technology

An A-to-Z Guide



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Algae Biofuel

Algae fuel is advanced biofuel produced by algae, small, mostly photosynthetic organisms that consist of one to a few cells. Some are more closely related to bacteria than to plants. In the process of photosynthesis algae convert carbon dioxide (CO_2), nutrients and sunlight into oxygen and biomass, including oil. This is achieved in a highly efficient way and it is estimated that the production of oil from algae could be 10 to 100 times higher than second-generation seed-oil crops, up to 200 barrels per hectare per year. Also heterotrophic (non-photosynthetic) algae can be utilized for oil production. Fossil algae may have produced our crude oil.

The reason why algae produce lipids is still unknown. The lipid oil droplets in diatoms might counter the weight of the dense silica shell and provide buoyancy. But during nitrate depletion some species change from neutrally buoyant to sinking in spite of increased oil production. Other hypotheses see the lipid pool as reserve products; but the algae also contain significant reserves of polysaccharides. The compromise might be that oil droplets assist the long-term survival in poor environmental conditions, while polysaccharides cover short-term energy needs.

Most algae store oil droplets inside; so to extract the oil the algae must be dried and centrifuged. The dry mass factor, i.e., percentage of dry biomass in relation to the fresh biomass, is economically important. Some algae species (*Botryococcus sp.*) secrete their lipids (long chain alkenes) outside their cells. It is relatively easy to separate the oil without killing the cells. Unfortunately, oil secreting species grow much slower than other fast algae. Selective breeding or genetic modification might overcome this limitation.

Algae react to adverse environmental conditions by producing hydrocarbons. The lipid content increases with age, and is dependent on temperature or salinity conditions, 'dark phases' (diatoms kept in the dark produce more oil droplets), nitrogen depletion (increases fat production), and drying or desiccation (increases oil production). Selected additives influence which lipids are produced (e.g. organic mercury and cadmium).

The generation of algae biofuels is achieved in bioreactors, transparent tanks with nutrient enriched water. CO_2 is added and the algae are illuminated with sunlight. In this environment an oxygenetic photosynthetic reaction is performed by the chlorophyll containing algae. The equation for photosynthesis is $6CO_2 + 6H_2O \Rightarrow C_6H_{12}O_6 + 6O_2$; energy required: 2870 kilojoules/mole (provided by light). Heterotrophic algae can be grown in high densities in containers without any illumination but need energy provided as sugar (glucose).

The classical bioreactor is the 'open pond'. It is simple but allows little control of algal population, takes much space, and large scale production is difficult. High performance bioreactors are closed systems that allow better control/protection of the algae. Three kinds of bioreactors differ slightly in cultivation (intensity of sunlight energy, mass transport, size) and production schemes (batch or continuous).

The 'plate photo bioreactor' consists of a series of transparent panels that are arranged to

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achieve a large illumination-surface area. This system is suitable for outdoor cultures and offers good biomass productivity at relatively low cost. Usually the CO_2 and nutrient fluid are injected at the bottom of the panels. As the system is rather flat, it requires sophisticated support infrastructure; also temperature control and 'wall growth' are issues.

A 'tubular photo bioreactor' is a system of connected, transparent tubes with the algae-suspended in circulating fluid. It is suitable for outdoor production and offers a large illumination-surface area in combination with good, continuous biomass productivity at low cost. However, constant pump circulation, which usually introduces gas and nutrients, leads to deficiency of CO_2 and a high concentration of oxygen at the end of the circulation. Fouling and some degree of wall growth result.

A 'bubble column photo bioreactor' is a large transparent vertical column. Gas and nutrients are injected at the bottom. The turbulent stream created by the rising bubbles allows good gas exchange, a high mass transfer and good mixing with low shear stress. The system is easy to sterilize, readily tempered and reduces wall growth. The main problem is the small illumination surface area, especially upon scale-up. Large systems might require internal illumination, limiting outside use.

The supply of nutrients is difficult. As freshwater is precious the use of waste water might be a very good alternative. But – as the algae are rather sensitive to contamination – the fluids must first be processed by bacteria, through anaerobic digestion. This increases the complexity of the system. The provision of CO_2 may become a major problem, as concentrated sources are usually from fossil fuels, and therefore not sustainable (except for CO_2 capture). Solar panels containing diatoms or other algae, utilizing atmospheric CO_2, that secrete gasoline rather than provide electricity or hot water, have been envisaged.

Large scale algae fuel production facilities are still in the development phase. Engineering challenges remain, especially in scaling and dewatering technology. Power companies have established research facilities with algae photobioreactors. The focus here lies on the scaling of the production systems from laboratory dimensions to mass production. Another goal of the research is to find out how efficiently algae fuel production could reduce CO_2 emissions and how much biomass will be produced. Algae biomass byproduct can be sold as fertilizer, animal feed or for pharmaceuticals to generate additional income. The emission reduction can be certified and converted into emission credits that can be sold to industry.

The potential importance of algae in the generation of oil and hydrocarbons has been illustrated best with an estimate by the United States Department of Energy (DOE). It states that - if all the petroleum fuel needed in the United States were substituted by algae fuel - it would require only about 40,000 km^2 of land, less than 15% of the area where corn is harvested. Algae fuel has the potential to be the most cost-effective renewable alternative energy source on the planet. However, investment in alternative fuels rises and falls with price changes for crude oil. For example, the USA halted a 15 year algal fuel project in 1995.

See Also: Appliances, Photo bioreactor, Energy Efficient; Appropriate technology,

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Biotechnology, Cellulosic Biofuels, Geoengineering, Green chemistry, Nanotechnology, Green, Passive solar, Sustainable design, Systems theory, Waste water treatment.

Further Readings

Hartman, Eviana (2008-01-06): "A Promising Oil Alternative: Algae Energy". The Washington Post. Retrieved 2010-12-29.

Books LLC. "Algae Biofuels: Algal Fuel Producers, High Lipid Content Microalgae, Chevron Corporation, List of Algal Fuel Producers, *Botryococcus Braunii.*" Books LLC (2010)

Gordon, Richard (2011). Quitting cold turkey: rapid oil independence for the USA. In: The Science of Algal Fuels: Phycology, Geology, Biophotonics, Genomics and Nanotechnology. R. Gordon & J. Seckbach. Dordrecht, Springer.

Ramachandra, T.V., Durga Madhab Mahapatra, Karthick B. & Richard Gordon (2009). Milking diatoms for sustainable energy: biochemical engineering versus gasoline-secreting diatom solar panels. Industrial & Engineering Chemistry Research 48, 8769-8788.

Sheehan, John; Dunahay, Terri; Benemann, John; Roessler, Paul. A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae, Close-Out Report [NREL/TP-580-24190], National Renewable Energy Laboratory, Golden, CO, 1998.

Ugwu, C.U., H. Aoyagi & H. Uchiyama (2008). Photobioreactors for mass cultivation of algae. Bioresource Technology 99(10), 4021-4028.

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About the Editors

Green Series Editor: Paul Robbins

Paul Robbins is a professor and the director of the University of Arizona School of Geography and Development. He earned his Ph.D. in Geography in 1996 from Clark University. He is general editor of the *Encyclopedia of Environment and Society* (2007) and author of several books, including *Environment and Society: A Critical Introduction* (2010), *Lawn People: How Grasses, Weeds, and Chemical Make Us Who We Are* (2007), and *Political Ecology: A Critical Introduction* (2004).

Robbins's research centers on the relationships between individuals (homeowners, hunters, professional foresters), environmental actors (lawns, elk, mesquite trees), and the institutions that connect them. He and his students seek to explain human environmental practices and knowledge, the influence nonhumans have on human behavior and organization, and the implications these interactions hold for ecosystem health, local community, and social justice. Past projects have examined chemical use in the suburban United States, elk management in Montana, forest product collection in New England, and wolf conservation in India.

Green Technology General Editor: Dustin Mulvaney

Dustin Mulvaney is a Science, Technology, and Society postdoctoral scholar at the University of California, Berkeley, in the Department of Environmental Science, Policy, and Management. His current research focuses on the construction metrics that characterize the life-cycle impacts of emerging renewable energy technologies. He is interested in how life-cycle assessments focus on material and energy flows and exclude people from the analysis, and how these metrics are used to influence investment, policy, and social resistance. Building off his work with the Silicon Valley Toxics Coalition's "just and sustainable solar industry" campaign, he is looking at how risks from the use of nanotechnology are addressed within the solar photovoltaic industry. Mulvaney also draws on his dissertation research on agricultural biotechnology governance to inform how policies to mitigate risks of genetically engineered biofuels are shaped by investors, policymakers, scientists, and social movements.

Mulvaney holds a Ph.D. in Environmental Studies from the University of California, Santa Cruz, and a Master of Science in Environmental Policy and a Bachelor's Degree in Chemical Engineering, both from the New Jersey Institute of Technology. Mulvaney's previous work experience includes time with a Fortune 500 chemical company working on sulfur dioxide emissions reduction, and with a bioremediation start-up that developed technology to clean groundwater pollutants like benzene and MTBE.

Introduction

What sets humans apart from other living organisms on our planet is the use of technology. *Technology*'s etymology derives from the Greek root *techne*, which means craft or art, and the root *-ology* conveys a discipline or field of study. We use technology to grow and prepare food, clothe and house our families, distribute our resources through markets and other financial mechanisms, transport us across the planet and beyond, and to keep us busy and entertain us. Technology has improved the living standards and life expectancy of humans, albeit unevenly. However, technology has given humans the ability to alter and transform Earth in ways previously unimaginable. We can put humans into space, turn mountains into valleys, and transport oil from miles below the sea. Our civilization's rapacious appetite for things and energy has brought considerable disturbance to the Earth's climate and ecosystems, particularly from industrial processes and land use change for agriculture. The evolution of technology has been anything but green.

Yet many argue that it will be green technology that saves human civilization and the planet as it replaces conventional technologies with more environmentally benign ones. As the human–environment relationship evolves, it is possible that technologies can be deployed to make that relationship more sustainable. Renewable energy promises to lessen our impacts to the extent to which it can be deployed. More efficient resource utilization through phenomena like industrial symbiosis and cradle-to-cradle design will lead to materials reuse and recovery, and will lower rates of raw material acquisition. Smart grids, for example, are designed to utilize energy more efficiently and encourage more energy conservation. It is also argued that green markets will drive change and innovation as the environmental externalities created by the economy are internalized, and as market prices reflect the environmental costs of doing business.

This volume's articles explore subjects related to our understanding of the ways that technologies coproduce human civilization and vice versa. There are explicit definitions of particular green technologies: for example, types of solar photovoltaic cells, algae biofuels, and white roofs. But the volume also integrates concepts and frameworks for looking at the interface between technology, society, and the environment. Many of these frameworks are derived from the related fields of the history of technology, science and technology studies, and industrial ecology. These intellectual traditions have deep roots in Marxism and other classical sociological, historical, and anthropological traditions.

Marx argued that technological development in capitalist society is exploitative and alienating. But he remained committed to the idea that working-class struggles can regain control of technological development to suit the purpose of the masses. More contemporary scholars reject the teleology of Marx, and destabilize the notion that technologies are motivated by, and behave in intended ways. Actor-network theory, for example, is a framework that emphasizes contingency and unintended consequences in technological design and deployment.

From what green technology has to offer, it remains difficult to distinguish fact from fiction, and utopian visions from the status quo. Clean coal, for example, is cast as a green technology based on reduced carbon emissions, but how does coal impact the environment through its life cycle? To what extent does solar photovoltaic technology adoption simply let people off the hook for their energy (over)consumption? With the lower carbon emissions involved with nuclear power, does this make it a green technology? Geoengineering likewise promises to bring us out of the climate change quagmire, but could also have uncertain and possibly severe impacts. Nanotechnology might be green for one person's ecological footprint, but it might also create occupational burdens in the manufacturing phase. Which technologies have impacts that are considerable and real? Can they be designed to mitigate these impacts?

Other green technologies are less embroiled in controversy. Green manufacturing, which embraces principles of product stewardship and ecological design, is one important development in green technology deployment. Green chemistry, which looks to substitute toxic chemicals for safer ones, also fits the green technology rubric, as does industrial symbiosis, which looks to employ principles of ecological to industrial systems. Design for recycling practices asks manufacturers to consider the end of life of their products to improve the ease of recycling and to avoid the issues associated with e-waste.

However, truly green technology might be something more transformative. It would change our behaviors and even our needs, instead of simply trading out one technology for one with lower impacts, a notion described as ecological modernization. Taken quite literally, the notion implies that the modernization of industrial society is becoming more and more ecologically minded, even though in practice it more closely resembles technological substitution. Likewise, a truly green technology would be one that is participatory in design and implementation.

Some argue that technologies need to be small, low impact, and decentralized to be green. E. F. Schumacher argued that "small is beautiful." These are echoes from the appropriate technology movement that advocates decentralized solar power, rainwater harvesting systems, biogas, and Earthships. They argue that some centralized technologies like nuclear power have authoritarian tendencies.

There are many questions regarding green technology. What does it mean? How do we assess its impacts? Who gets to define, develop, and benefit from green technology? We hope this volume helps the intrigued reader think through these questions. Answers to these questions are not entirely straightforward as technologies are entangled in politics, culture, and the economy, in addition to the biophysical systems that support human civilization. Yet embracing green technology is possible and even defensible as long as the social and environmental dimensions are carefully evaluated. But even then, technologies can have implications that are not by design.

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Kessler, Eric A. "Does Waste Heat Recovery Make 'Cents'?" *Process Heating*. http://www.process-heating.com/CDA/Archives/8b6e827d50368010VgnVCM100000f932a8c0 (Accessed September 2010).

Sakraida, Vincent A. " Basics for Absorption Chillers." *Engineered Systems*. http://www.esmagazine.com/Articles/Feature_Article/BNP_GUID_9-5-2006_A_10000000000000539128 (Accessed September 2010).

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See Also: Appliances, Energy Efficient; Appropriate Technology; Biotechnology; Cellulosic Biofuels; Geoengineering; Green Chemistry; Green Nanotechnology; Passive Solar; Sustainable Design; Systems Theory; Wastewater Treatment.

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Hartman, Eviana. "A Promising Oil Alternative: Algae Energy." *Washington Post* (January 6, 2001).

Ramachandra, T. V., Karthick B. Durga Madhab Mahapatra, and Richard Gordon. "Milking Diatoms for Sustainable Energy: Biochemical Engineering Versus Gasoline-Secreting Diatom Solar Panels." *Industrial & Engineering Chemistry Research*, 48 (2009).

Sheehan, John, Terri Dunahay, John Benemann, and Paul Roessler. "A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel From Algae, Close-Out Report." NREL/TP-580-24190. Golden, CO: National Renewable Energy Laboratory, 1998.

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Anaerobic Digestion

Anaerobic digestion is the breakdown of organic matter via microorganisms in the absence of oxygen, which results in the generation of carbon dioxide (CO_2) and methane (CH_4). Materials high in organic content, such as municipal wastewater, livestock waste, agricultural waste, and food wastes, may all undergo anaerobic digestion. The methane gas produced may be collected and used directly as a fuel for cooking or heat, or it can be used to generate electricity. Unlike the production of methane from gas wells, anaerobic digestion is a renewable source of energy.

Anaerobic Digestion Feedstocks

Several feedstocks exist for the anaerobic digestion process, all of which contain organic matter, including municipal and animal wastewaters and agricultural and food wastes. Anaerobic digestion is frequently used in the treatment of municipal wastewaters, often in a series of process steps that also include aerobic digestion (digestion in the presence of oxygen) and sedimentation. The amount of solids produced from the wastewater treatment can be reduced though anaerobic digestion, which in turn reduces the costs associated with solids disposal. Similar to human waste, animal waste may also provide the feedstock for anaerobic digestion.