Short-circuiting our fossil fuel habits

Could a more direct harnessing of photosynthesis become an alternative to natural oil, coal and gas?

In hindsight, 2004 could be the year that finally made us aware of our perilous addiction to crude oil. The war in Iraq, global shortages in supply, jittery traders and decreasing confidence in global supplies saw oil and natural gas prices rocket to levels not seen since the oil crisis of 1977. Experts increasingly agree that we are probably in sight of, or even sitting on, the crest of peak production of crude oil: from here on it is all downhill. "Finally!" say the proponents of renewable energies, and researchers working on possible alternatives to fossil fuels. But it is not merely the imminent shortage of crude oil, the greenhouse effect and pollution that are driving research in bioenergy; there are genuinely better—in all senses of the word—ways of generating energy on the horizon.

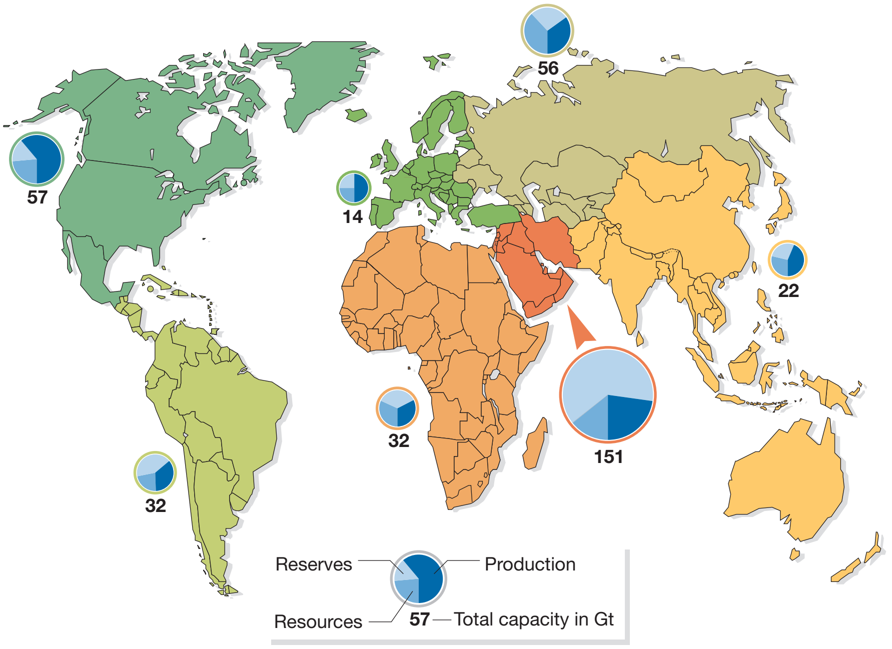

Fig 1 | Estimated global resources of crude oil. Source: Federal Institute for Geosciences and Natural Resources, Hanover, Germany.

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While the sun is still shining, and the earth is still orbiting it, all energy on the planet is, in principle, renewable. The problem is that some sources of energy, such as oil, coal and natural gas, take millennia to renew. Research into new biological sources of energy therefore seeks to short-circuit the time needed to turn sunlight into usable energy. The essential principle in harnessing the sun's energy is always the same: the light-induced excitation of an electron in a pigment molecule. Sunlight is free, and, in evolutionary terms, life on earth did not take long to capitalize on this energy source: the first photosynthesizing organisms probably arose more than 2.5 billion years ago. Since then, our fossil fuel reserves have been continuously created by atmospheric carbon sinking into sedimentary rocks (Fig 1). However, over a period of only 400 years—if predictions hold—we will have liberated most of it again as carbon dioxide. The fact that this carbon dioxide cannot be recycled into organic matter fast enough to prevent global warming is clear. Whatever our source of carbon-based fuel, if our requirements remain as high as they are today, we will continue to overload natural recycling mechanisms. Cutting energy consumption globally, at a time when it is rising in tune with developing economies, is simply not feasible. We need to find alternatives to carbon-based fuels as well as promote systems that are cost-neutral in terms of the carbon cycle.

One of the attractions of turning biomass directly into energy is that it does not release additional carbon dioxide. Self-sufficient, decentralized energy production that uses biomass works on the principle that the material being fermented into methane and burnt is already growing again in local fields. Such a system has been developed by the Interdisciplinary Centre for Sustainable Development (ICSD) in Göttingen, Germany, using a model community in Lower Saxony. Bioenergy Village Jühnde (Fig 2) with 770 inhabitants, uses a biomass fermenter that turns plant material into methane and a combined heat and power station that burns the gas. The lights went on at the end of 2004, and the power plant is already generating twice as much electricity and exactly as much heating as the community needs. Hans Ruppert, Professor of Geosciences at the University of Göttingen and ICSD board member and project leader, said his main motivation in starting the Jühnde project was a deep concern for the way energy usage in the developed world threatens to create geo-social conflicts caused by imbalances in economies and the climate.

A totally self-sufficient entity, the Jühnde plant takes biomass from local fields and uses the post-fermentation residue as fertilizer. Because any kind of biomass will do, fields of weeds can be grown for the purpose, thereby

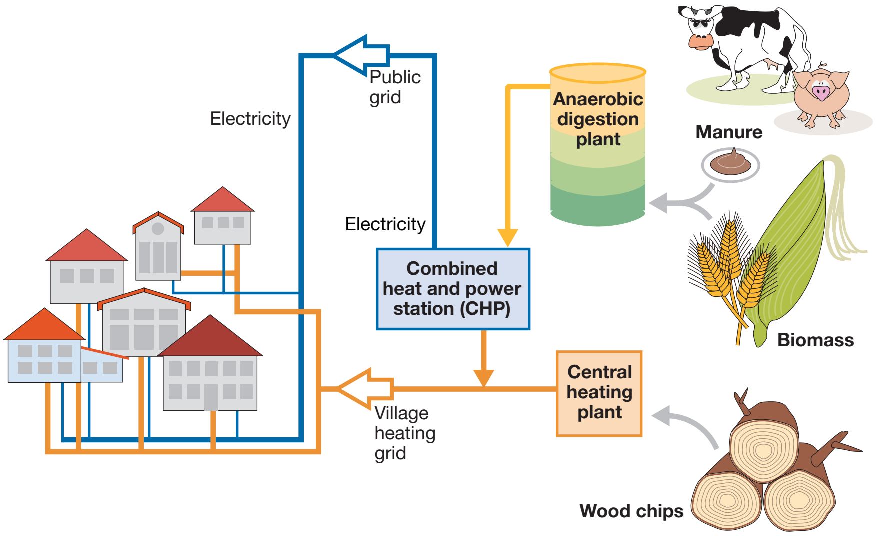

Fig 2 | Concept of the Bioenergy Village Jühnde.

additionally conserving natural biodiversity and reducing pesticide use. Indeed, by harvesting plants before they seed, two crops of biomass can be grown per year. It has been estimated that such decentralized plants could produce up to 25% of Germany's entire electricity demand. But equally important as numbers and proof-of-principle is the social value of the project: the sense of community pride and responsibility. "With contaminated food scares, BSE and similar troubles, rural areas have suffered a great decline in respect in recent years; we want to give them a chance for the future, and restore the level of respect they receive from the rest of society," Ruppert remarked. In addition to the subsidies granted by the German government in support of renewable energy production, this could become another driving force for farmers and rural communities to establish such decentralized energy production plants: sometimes urban dwellers do not respect or value farmers for producing food, but perhaps they would if these very farmers made the electricity that powered their lights, cookers and washing machines. Also, subsidies for growing fuel crops would certainly please voters more than the current EC farming subsidies that largely go into excess production. Many other villages in Lower Saxony and Northrhine-Westfalia have shown interest in becoming Bioenergy Villages, and even Japanese and Chinese delegations have visited Jühnde to study the technology.

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Although this is a promising start at the level of rural communities, other strategies are required to fulfil the global demand for portable energy. For several decades to come, transportation and many other industry sectors will have to rely on fossil fuels, as there is no immediately feasible alternative. As Wolfgang Steiger, lead researcher for energy conversion at the German carmaker Volkswagen (Wolfsburg, Germany) commented, "technologies have to be focused on the short to mid-term area in order to be compatible with current infrastructures." Market forces are the other factor: although diesel engines have a greater efficiency than petrol engines, and 50% of cars now sold in Europe run on diesel, the cumulative value of the market is still only 10%; that is why a complete switch to diesel will not happen overnight. However, diesel may well become a short-term solution for global shortages of fossil fuels, because it is the preferential product of hydrocarbon fuel production from plant material.

If Bodo Wolf, a coal engineer from Freiberg, Saxony, in Germany, realizes his dream, diesel cars of the future will all burn 'SunDiesel'. This fuel is produced from agricultural biomass by high-temperature extraction of synthesis gas (carbon monoxide and hydrogen), which is then catalytically 'cracked' into petroleum-like hydrocarbons. Wolf, who pioneered this process, is now working on a semi-economic scale at a plant called Choren Industries in Freiberg, Germany—an acronym of C H O renewable energies. By 2008, the business plans to produce 225 million litres per year of the cleaner-burning diesel from wood, straw and other plant waste.

Seen in terms of carbon dioxide efficiency—that is, the ratio of carbon dioxide emission to production price—SunDiesel achieves a balance of 85% from biomass itself and 15% from fossil-fuel energy. The only low-temperature biomass conversion process that can approach this level of efficiency is the as yet experimental production of ethanol from lignocellulose—a complex fibrous material consisting of cellulose and hemicellulose highly cross-linked with lignin. However, this is still far from applicable at industrial scales. In the next 30 years, therefore, Volkswagen's Steiger sees diesel from biomass accounting for as much as 25% of the total automobile fuel requirements (Fig 3).

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With China and India dramatically increasing their consumption of fossil fuels over the next 20 years, Steiger believes that "we shouldn't think in terms of either/or solutions; we need roughly everything we can lay our hands on to get away from fossil fuels." Big car companies, such as Volkswagen, General Motors (Detroit, MI, USA) or DaimlerChrysler (Stuttgart, Germany) are already consistently moving in the direction of cleaner, renewable fuels, and perhaps by the year 2030 we will see some economically feasible hydrogen cars on our roads. But as Steiger concludes "to introduce a big new technology, such as fuel cells, we need a huge amount of time to achieve a measurable share of the market."

Many problems of alternative energy production rest on storing energy in a form that can be used later with minimum pollution. So far, green plants have stored energy for us in the form of reduced carbon, such as fossil fuels. However, the chemistry of photosynthesis itself has long suggested that some tinkering could engineer it to produce electricity directly, or even hydrogen. At the heart of the photosynthetic process is photosystem II (PS II)'s capacity to absorb light at 680 nm, eject excited electrons and replace them by stealing electrons from nearby water molecules, splitting them to give protons and oxygen (the Hill reaction). Photosystem I (PS I) absorbs light at 700 nm, and takes electrons from PS II, exciting them even further and producing chemical intermediates needed for energy and biosynthesis of carbohydrates (ATP and NADH). But there is no point going to the lengths of splitting water, only to combine hydrogen with carbon dioxide to make carbohydrates—unless, that is, one is a tree. Instead, plug the excited, high-energy electrons into a circuit in which they can return to a low-energy acceptor, thereby creating a battery.

Proof of this principle was delivered last year by Shuguang Zhang, Associate Director of the Center for Biomedical Engineering at the Massachusetts Institute of Technology (Cambridge, MA, USA), and co-workers, who reported a photovoltaic cell based on PS I extracted from spinach. It is too soon to say whether the chlorophyll can survive long enough to make the cells viable; the longest continuous experiment so far—three weeks—was stopped for other reasons. But it was already a great achievement, as PS I, which consists of 167 molecules of chlorophyll, has to be arranged in an exquisitely regular formation to work. Using specially designed peptides with surfactant properties, Zhang succeeded in stabilizing the complex natural arrangement of chlorophyll molecules in PS I, which is normally embedded in a biological membrane. “Even the smallest distortion [of the natural alignment] of photosystem I destroys the function,” he said. Although the 1 cm square chip produces only a few nanoAmperes of current, Zhang believes that applying thousands of layers, and extending the chip in three dimensions, will increase power output in a disproportionate way, easily reaching the milliAmpere range that current silicon-based photovoltaic devices achieve.

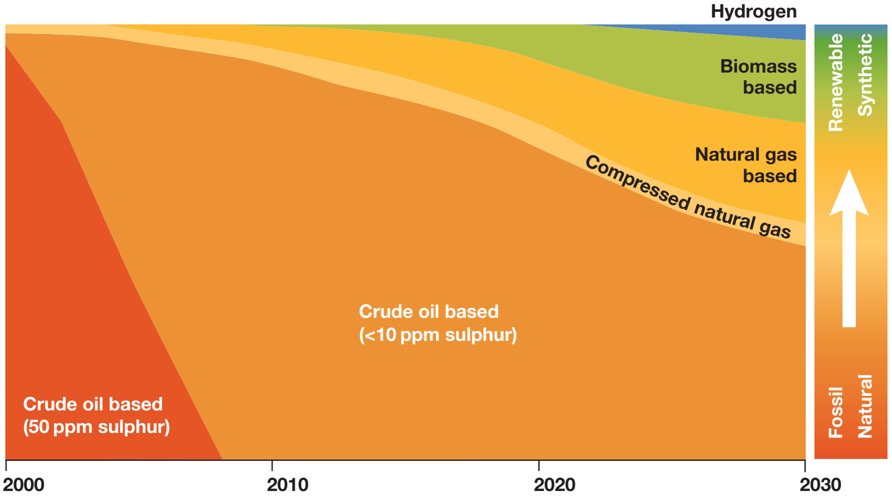

Fig 3 | Possible scenario of future fuel diversification in Europe. Source: Volkswagen AG, Wolfsburg, Germany.

Because self-assembling nanotechnology arranges the individual PS I units in an ordered fashion, a much higher density of photoactive sites can be achieved than with a silicon chip—and the result is also lighter per unit active surface. But further development depends on investments that neither the US National Science Foundation (especially after recent cuts), nor US industry are prepared to make. “US industry has shown no interest at all,” lamented Zhang, “but Japanese and European companies are curious.” However, he will not be put off, as the potential to harness solar energy directly is simply enormous: “we are capturing as little as one trillionth of the possible solar energy hitting the planet”. Next he plans a trip to Japan to study chlorophyll in marine algae living 20 m deep, which might be even better than spinach at capturing solar energy.

Despite being four times as efficient at energy conversion as the best silicon-based photovoltaic system, chlorophyll has acted more as the inspiration than the construction material in another branch of research known as ‘artificial photosynthesis’ (AP). Working with synthetic pigments embedded in a crystalline metal oxide membrane to produce electricity from sunlight, Michael Grätzel and co-workers at the Swiss Federal Institute of Technology in Lausanne are well on the way to making AP an everyday reality. Indeed, so excited were Australians about the Swiss technology that the company Sustainable Technologies International (Queanbeyan, NSW, Australia) licensed it and has already started the world's first production facility making AP solar panels (www.sta.com.au). Grätzel has licensed the technology to another nine companies worldwide. The chlorophyll analogue, a light-absorbing organic ruthenium complex, is deposited in a thin matrix layer made of nanocrystalline titanium dioxide. Layers are stacked to increase their light-absorbing ability, similarly to the chlorophyll-rich thylakoid membranes in plant chloroplasts. Simply by adding more layers, Grätzel says, one can obtain films that absorb 99% incident light, and the brown translucent panels make “very nice architectural elements”.

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But unlike a plant leaf, which reaches saturation at 30% of maximum sunlight, Grätzel must make a system that is linear up to 1.5 times maximum sunlight in order to capture reflected light as well. Plant photosystems are simply not up to the job, as they undergo photodegradation too quickly. Conduction of electrons in Grätzel's invention takes place in the tough nanocrystalline matrix, making it sufficiently robust. ‘Holes’ left by departing electrons are filled from the other side by an electron donor, and if the two sides are connected across an electrical load, then current flows. In nature, the hole left by a departing high-energy electron is used to oxidize water to oxygen and protons, and this opens yet another tantalizing possibility: the direct production of hydrogen in a photocatalytic reaction.

“I think in the long run you will see more photosynthetic systems making hydride or hydrogen,” said Grätzel. But for economically interesting output, the photoreactive centres need to last around 20 years, surviving 100 million cycles. At present, only ruthenium complexes have demonstrated this tenacity, but Grätzel noted that replacing magnesium ions with copper ions in chlorophyll substantially increases its stability with no reduction in photoreactivity. “We don’t just have to drop biological ideas and say now we’re going all silicon; we should also look into thermophilic bacteria [for more stable electron transport systems],” Grätzel pointed out. “Studying plants has always been a big inspiration for us; we all admire the plants, and we’ll see more of that—research from photosynthesis has very much driven this field.”

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Laptop biology

As mathematics and computation increasingly invade laboratories, biologists need to master new skills

It is a common sight these days in the cafeterias of biological research institutes: a group of scientists sitting around a laptop computer discussing their results. Even in the laboratory, biologists now spend more time in front of a computer screen—not only to read the latest literature, but also to plan experiments or analyse results. The invasion of computers is just one visible aspect of a growing trend in the life sciences: research is becoming more analytical and multidisciplinary. This transformation from a ‘soft’ science based largely on experimentation, classification, observation and intuition into a ‘hard’ science involving mathematics and algorithms, has profound consequences on the skills required in both the laboratory and the clinic. Biologists increasingly have to master mathematical modelling, statistical analysis, image processing algorithms and 3D visualization, while mathematicians and physicists need at least graduate-level biology to engage seriously in the life sciences.

These changes have spanned at least half a century, since X-ray crystallography was first used to reveal the structure of myoglobin, a feat that required collaboration between mathematicians and physicists (Kendrew *et al*, 1958). But it took years before such interdisciplinary cooperation became commonplace, and it is only recently that some knowledge of mathematics and computation has become essential in almost all branches of biology.

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Experiments and observations remain at the core of biological research, but they now intersect more closely with theory—a situation that mirrors the development of physics a century ago. “I see biologists becoming rather like particle physicists,” said Denis Noble, Professor of Physiology at Oxford University, UK, who specializes in computer models of biological organs. Noble argues that, more and more, experiments in biology are being conducted only after models to predict their outcome have been developed, as is the case in particle physics. This is necessary to minimize the number of expensive experiments and to ensure that they proceed along the right path.

For research biologists in the laboratory, or clinicians treating patients, the obvious question is to what extent they need to acquire expertise and knowledge in mathematical modelling, computation and statistical analysis and how much of it can be left to specialists. The answer is that analysis is now an integral part of biology, and it is increasingly impossible for biologists to remain ignorant of mathematics. “For biologists to know which data to gather, they need to have some idea of what modelling is,” said Philip Maini, a professor at the Centre for Mathematical Biology at Oxford University, UK. He argues that experimentalists in biology have only recently started to acknowledge the relevance of theory. Before that, there was a tendency to be easily carried away by the latest techniques for making measurements without thinking sufficiently about whether they were collecting the right data, just as theoreticians may be seduced by what appears to be a beautiful model while ignoring the underlying biology. However, Maini has noticed signs of a growing appreciation on both sides of the need for greater rapport between theory and experiment. “For example, at a recent gathering the experimentalists were getting very excited about what techniques and measurements they could use when one of them said, ‘But are any of these measurements going to be useful for the mathematicians?’ This is the first time I have heard an experimentalist say this and it is an example of how things are changing,” Maini commented.

In turn, mathematical models inform experimentalists and encourage them to explore new avenues that they might otherwise have neglected. An example of this feedback from model to experiment is a device for measuring the electrical and mechanical properties of a single myocardial (heart muscle) cell, developed by Akinori Noma, a well-known pioneer in biological simulation at Kyoto University (Japan; Hassan *et al*, 2004). His team

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