

# BBSRC Sustainable Bioenergy Scenario Tool

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## Introduction

One of the major challenges facing humanity over the next half century is the development of new energy technologies. This is driven by two major concerns. First, it is widely accepted that, within this period, conventional fossil fuel resources will cease to meet global energy needs, whether by the exhaustion of reserves or by sharp increases in the costs of extraction from less accessible, and possibly less secure, locations. Constraints on the availability of hydrocarbons would also increase competition between their use as energy sources and as feedstocks for the plastics industry. New technologies would improve the security of energy supplies and allow a scarce resource to be reserved for those purposes to which it is uniquely suited. Second, although contested in some quarters, there is also strong evidence of an increasing threat from global climate change. The continuing release of CO<sub>2</sub> from fossil fuels is thought to be a major contributor to the atmospheric changes associated with this threat and there is a clear policy demand to develop sustainable fuel technologies as part of a transition to forms of social and economic organization that generate lower carbon emissions.

While these challenges may be met, in part, by measures to reduce energy demand through increasingly efficient use of existing technologies, these are unlikely to match the growing requirements of global economic development. In any case, common prudence dictates the desirability of investigating the potential of alternative technologies, given the unavoidable lead times in moving innovations from research sites into actual use. Bioenergy is one such technology and is currently the subject of about £43 million investment by BBSRC, in partnership with industry. This basic research into a wide range of potential biological sources of energy, and feedstocks, is laying the foundation for products that can begin to make a contribution to meeting global demand sometime in the 2020s.

## Innovation and Public Engagement

It is increasingly acknowledged that successful innovation is not purely a matter of high-quality scientific research but also requires favourable social and economic conditions. This has been underlined several times in the biotechnology sector where innovations like irradiation for preserving food or genetic modification of crops to increase their range or productivity faltered in their introduction to the market because of public concerns. The initial response from scientists and science policy makers was to address these

concerns through the rational provision of information, assuming that negative public reactions were driven by ignorance of the 'true facts'. This so-called 'deficit model' proved wide of the mark as social scientific research showed that the public response reflected different value choices and socio-economic priorities rather than a lack of understanding of the scientific developments: ordinary people might not know every detail of what was involved in the modification of plant genomes but they could grasp this at a sufficient level to make their own informed appraisal of the potential risks and benefits, weighted according to their own preferences rather than those of the developers or investors in the technology.

In recent years, then, the focus has shifted to what has become known as 'upstream engagement', where scientists and their backers are encouraged to enter into a dialogue about emerging developments that allows public thinking to influence research programmes at an early stage, for problems to be identified and solutions negotiated on the basis of a mutual understanding of technological possibilities and socio-economic concerns. In effect, this is an extension of a process that has always existed between scientists and their patrons but which is now enlarged, reflecting both the role of public investment and of consumer involvement, to encompass a much wider group of stakeholders. The goal is to ensure that end-users will never again be presented with a *fait accompli*, a new technology that is rolled out with little prior warning or debate, leading to a high risk of suspicion and resistance that negates the time, energy, creativity and other resources that have been invested in its development.

Bioenergy has already been the subject of some critical responses, particularly over concerns that the use of land for growing biomass crops has been crowding out the production of food crops. This is claimed to have contributed to food supply shortages leading to increases in world prices resulting in lack of access to food and civil disorder in some of the poorest countries. These issues have recently been explored in a report from the Nuffield Council on Bioethics (Nuffield Council on Bioethics 2011), which raised a number of important questions about the implications, although acknowledging that the evidence of harm was not conclusive. The technologies being explored with BBSRC investments are, however, so-called 'second' or 'third' generation, which do not depend on biomass crops, and which are accepted as less likely to raise issues of ethical concern. They are mostly directed towards the use of inedible elements and other waste from food

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crops or to the use of non-food feedstocks such as algae. Nevertheless, it remains important that the social and economic implications of this potential switch in energy sources are understood and debated at an early stage in the programme.

## The Role of this Document

This document forms part of a set of tools that has been produced by BBSRC to support public dialogue about the future course of research and development in bioenergy. It is anticipated that it will be used as part of that tool-kit, although, of course, different selections may be made to suit different groups of participants. Scenarios are a valuable resource for many groups. Although policymakers set great store by quantitative models, these can be difficult for others to use, because of the problems in envisaging how their outputs will actually be reflected in the experience of everyday life. Models can also have a deceptive objectivity because they obscure the choices that have been made in the selection of variables and in the algorithms that link them together. For some planning purposes they are essential – but they are not necessarily the best tools to use in public dialogue events. The approach developed here is likely to be most appropriate for activities with students in secondary schools, with community groups and possibly with mid-level policymakers. Although the scenarios offered in this document can be used directly with any of these groups, an important aspect of this approach is that it encourages creativity on the part of whoever is facilitating the dialogue. There are far more pathways into the future than can be captured by just four scenarios and the document shows how these can be used as illustrations of what can be done and explains how users can adapt and develop the approach to suit their own interests and those of the groups with which they are working.

We begin, then, with an explanation of the scenario approach and how the scenarios have been constructed. This is followed by four demonstration scenarios with suggestions about how these might be used by facilitators who do not want to adapt them further. Finally, there are two chapters giving more details about the evidence base and where further resources can be found for users who are interested in creating their own scenarios or in understanding more about the choices that have been illustrated in the four that have been presented.

## Chapter 1 Designing and Using Scenarios

Scenario development needs to take account of both technological and contextual pathways into the future, defined here as 2030. This cut-off date will help facilitators focus public groups on actions that will have direct implications for them or for people known to them who are alive today. There is nothing sacrosanct about the date, and if this document proves to have an extended life, users may wish to push it back. There are some disadvantages to an early date because of the long investment life of energy technologies but these seem to be outweighed by the ability to imagine oneself or one's immediate descendants living in a world only twenty years away. The 2050 cut-off favoured by other current scenario developers is much harder for anyone in mid-life to deal with and leaves more space for radically disruptive innovations to occur, whereas the energy technologies that will be used in 2030 are likely to be known, at some level, today. BBSRC, for example, envisages that a number of its present investments will be making an impact by the early 2020s.

As we have noted, technology does not stand apart from its context. The possible futures for bioenergy will reflect the overall level of energy demand – driven by national and global population and economic growth, the availability and attractiveness of other fuels or feedstocks, the resources available for investment, the impact of climate change on growing environments, etc. While these need to be reduced to a manageable set of variables for any particular scenario, their absence leads to the production of rather simplistic technological Utopias where it is assumed that a single technology will move unproblematically into use and that users will reshape their lives and institutions around it. This is just not how technology adoption works: it is always an interaction where users adapt technologies as much as technologies adapt users. It may be helpful to think of this in terms of a matrix.

		Context		
		Adverse	Neutral	Favourable
Technology	Failure			
	Modest progress			
	Success			

For any given technology, there is a set of scientific possibilities. For example, the current efficiency of photosynthesis is about 6%. Biotechnological innovation may find ways to increase this under laboratory conditions that cannot be recreated in industrial-scale production and the technology fails to come into use. The efficiency may be doubled to 12% but other energy technologies offer better returns for most applications and this pathway only leads to a few niche applications where a liquid fuel is essential, resulting in modest progress. Finally, there may be a major breakthrough in the genetic engineering of plant feedstocks which increases efficiency to 30% and this technology sweeps the board. However, the ability to achieve any of these outcomes will also be influenced by the level of funding available for R&D investment. If there were to be little growth in the UK economy over the next twenty years, much as has happened in Japan since the Asian economic crisis of the early 1990s, then the chances of achieving the breakthrough may be compromised – or it may occur in a part of the world that has seen more economic growth and been able to sustain higher levels of expenditure on R&D. Higher levels of expenditure may, of course, also mean more money spent on failures.

The matrix will help facilitators to ensure that technology and context are always considered together within any particular scenario as it is used or developed for any specific episode of dialogue or engagement. This example simplified 'context' to a single variable and we shall discuss later in the chapter how a range of variables must be assessed for their contribution to the columns of the matrix. Before doing so, however, it seems sensible to examine the plausible technology pathways. These represent the rows of the matrix. In principle, a scenario could be built around any of them, so that facilitators might hold the context constant and run different technologies against it. Alternatively, a technology could be held constant and considered in different contexts. Our review (See chapter 3) identified eight emerging or established biofuels. Given that this is a limited set, we suggest that the first decision for a facilitator should be to choose which pathway they want to put into the scenario.

## Technology

Eight biofuels seem plausible contenders for widespread adoption over the next twenty years.

### Bioethanol/ETBE

Ethanol is currently the dominant biofuel in scale of production and use. It is not an ideal fuel molecule, mostly because it is incompatible with the existing infrastructure for distribution and storage owing to its corrosivity and high hygroscopicity (ability to attract water molecules); moreover, it only yields about 70% of the energy content of petrol. As a result, other biofuels have begun to emerge as likely competitors or successors to ethanol and its future may lie more in substituting for oil as a chemical feedstock for plastics and similar applications. Nevertheless, it is being widely used in the US and Brazil, mainly as a replacement for petrol in the transport sector. Ethanol is produced for biofuel by the conversion of cellulosic biomass from feedstock crops including corn; rice; sugarcane; perennial grasses, such as switchgrass and giant miscanthus; and woody crops such as poplar and shrub willow.

ETBE, which is produced by a reaction between ethanol and isobutylene, can also be mixed with petrol, but is less prone to absorb moisture.

### Biomethanol and Biomethane

Methanol (also known as wood alcohol) is produced by a process using natural gas, of which methane is a major component, as a feedstock and has similar physical and chemical properties to ethanol. Methane gas can be generated by microbial action from biomass, which may come from a variety of sources. The substrate can be cow manure, manure from other farm animals such as pigs,

chickens and horses, fat from slaughter waste or frying oil, organic household or garden waste, municipal solid waste and rotten foodstuff. Even organic waste from hospitals containing paper and cotton, municipal sewage sludge, waste from agriculture or food production, organic-rich industrial waste water etc. can be used. Energy crops such as maize (whole plant including the corn), clover, grass, young poplar and willow may be grown for biogas production and added purely or in mixture. MTBE, the methanol equivalent of ETBE, has been used as a petrol additive in the past to enhance octane and create cleaner burning fuel but its production and use has declined because it has been found to contaminate ground water. Methanol has potential applications as a transport fuel but presents the same corrosion problems as ethanol in everyday use. It can also be used as a chemical feedstock. Methane gas is seen as a potential alternative to, or replacement for, natural gas in heating and cooking, although it could be used as a transport fuel in liquid form.

### Biohydrogen

This can be derived in a similar fashion to biomethane from organic waste materials, using different bacteria or algae in the fermentation process. The importance of biohydrogen is its potential use in hydrogen-powered vehicles, should this technology emerge as an important system for the transportation of passengers or light goods.

### Biobutanol

Butanol has a number of advantages over ethanol, especially in terms of transport. As a fuel mixture, it is more easily transported with petrol and diesel through pipelines because of its lower tendency to separate from the fuel when contaminated with water. Butanol has two more

Biofuel	Process	Status	Engine application
Bioethanol	Microbial	Industrial	Pure/blend
ETBE	Chemical/microbial	Industrial	Blend
Biomethanol	Thermochemical/microbial	Pilot plant	[Pure/blend] MTBE/biodiesel
Biobutanol	Microbial	Pilot plant/industrial (until ca 1990)	Pure/blend
Biomethane	Microbial	Industrial	Pure/blend
Biohydrogen	Microbial	Laboratory	Bioethanol (Syngas)/pure
Biodiesel	Physical/chemical (enzymatic)	Industrial (laboratory)	Pure/blend

Table from Antoni, Zverlov et al. (2007)

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carbons than ethanol, resulting in an energy content about 40% higher. It has been demonstrated that n-butanol can be used either 100% in unmodified 4-cycle ignition engines or blended up to at least 30% (70% diesel) in a diesel compression engine or to 20% (80% kerosene) in a jet turbine engine.

### **Biodiesel (FAME and FAEE)**

Biodiesel is a generic term for a number of fatty acid esters, of which the most important are FAME (fatty acid methyl esters) and FAEE (fatty acid ethyl esters). The main potential sources for the oils for conversion are vegetable oil; animal fats; and recycled grease from waste. Vegetable oil comes from seeds which are crushed to produce crude oil that can be filtered, and refined. In the US, soybean is the plant source of choice. Animal fats come from greases, meat, blood, feathers etcetera produced in slaughterhouses. Recycled grease comes from cooking oils from restaurants and food processors. Currently, biodiesel production uses plant oils for the vast majority of its starting material. It can be used in any existing application for diesel and refined into synthetic kerosene suitable for use in aviation.

### **Other:**

A range of other possible biofuels or feedstocks have been canvassed at various times including: ethers (DME, DMF); alkanes; alkenes; branched-chain alcohols; isobutanol; and isopropanol. None of these are currently exciting the same interest or level of investment as the processes discussed above, and they are not explored in detail here. Should there be developments over the lifetime of this document, however, any of these could be substituted on the technology axis of the matrix and used in exactly the same way as the examples shown later.

Most of the pathways discussed here look towards biofuels as substitutes for existing liquid fuels in transport, with the partial exception of biogas, the precursor of biomethane, which is seen to have potential as a domestic fuel for cooking or possibly heating. However, there is also likely to be competition for the use of fossil fuels as feedstocks for other products, particularly those based on ethanol and butanol. This is not well captured in many current projections which may, then, understate the demand for biomass. Scenarios should consider the implications of using biomass for purposes other than transport fuels, particularly as the transport sector is increasingly emphasising the importance of electrically-powered vehicles, including petrol or hydrogen hybrids, for many terrestrial purposes. Biofuels could be confined to niche applications in aviation and

off-road diesel use in agriculture, mining and construction, together possibly with long-distance road haulage unless this is displaced onto rail to a greater degree than currently seems plausible. Biomass could also be used directly in electricity generation, but this would require developments in combustion technology more than biotechnology, unless, for example, genetic modification were used to accelerate tree growth and coppicing cycles.

In discussing competing fuels and other sources of demand for biofuels, we are beginning to stray into considerations of context which are captured by the potential contents of the columns of the matrix.

## **Context**

The Context axis of the matrix presents many more choices for facilitators and offers much more scope to engage public groups with a variety of possible futures into which bioenergy will emerge. Having selected a biotechnology pathway, facilitators then need to consider how they can assemble contexts that will stimulate dialogue appropriate to the event. These contexts may be relatively mundane or they may deliberately exaggerate some possibilities in order to provoke discussion about the compromises that may need to be made in any real future. Scenarios are not forecasts or predictions: their value lies in confronting people who will be affected by technological developments with visions of possible futures, inviting them to consider the advantages and disadvantages and to explore ways in which desirable goals can be maximized and undesirable ones minimized.

## **Competing Energy Technologies**

The future for biofuels will be shaped in important ways by the development of other energy technologies that do not require the use of fossil fuels. In practice, most of these contribute to the generation of electricity, which is then a source-neutral means of transmitting energy to the end-user. Biomass may have a contribution here as material to be burnt in power stations, possibly in combination with fossil fuels, but the size of this contribution will reflect its cost and security of supply relative to other sources, and the relative amount of R&D investment directed towards each. These include (onshore and offshore) wind; hydro; tide; wave; geothermal; and solar. In the UK, some of these – hydro, tide, geothermal – offer relatively secure and stable generating capacity, while others – wind, wave, solar – are more intermittent and require some measure of back-up

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capacity, such as nuclear, to ensure continuity of supply, unless there are significant technological developments in storage technology. Solid or liquid biomass products, however, could be storable for this kind of back-up use without major innovation. Gaseous biomass products, to which may be added landfill and sewage gas as closely related sources, present more of a storage challenge, although the gas could be liquefied or pumped into underground reservoirs depleted by natural gas extraction. Consideration should also be given to the extent to which existing fossil fuel technologies may become more efficient or demand reduced by a roll-out of insulation and other measures to manage energy consumption.

As things presently stand, few people are arguing that biofuels will have a major role in large-scale power generation. They could, however, plausibly have a place in more distributed generation systems as a local source of easily storable back-up capacity or as an alternative to existing fossil fuels in off-grid locations, replacing diesel for domestic generation, for example. The key contest seems more likely to occur in transport applications, where liquid fuels are currently dominant and, in some applications, not substitutable. Even here, biofuels will contest the market with source-neutral electricity in battery-powered vehicles and with hydrogen, whether used directly in internal combustion engines or through fuel cells. Biomass could be one source of this hydrogen. There are, though, certain niches where liquid fuels that closely resemble existing technology are likely to be dominant through to 2030 and well beyond. Aviation is one of these, as are agriculture and other primary industries such as mining and quarrying, together with heavy long-distance haulage. If biofuels can be produced that closely resemble kerosene and diesel, they are likely to be the principal contributors to meeting energy demand from these sectors.

Scenarios need to take a view on the likely shape of the energy market and the relative progress of rival technologies up to 2030. Will biofuel alternatives to petrol develop more quickly than fuel cells so there is a mass market for a product that closely resembles those that the consumer is familiar with and which can be delivered through existing supply networks to drive vehicles with comparatively few modifications? If this happens, then a superior technology might fail simply because it comes second into the market and the niche has already been occupied. Will UK governments balk at the capital cost of rebuilding the rail network around electric power so that there continue to be substantial markets for biodiesel in long-distance passenger

and freight haulage? Will price and traffic management disincentives actually reduce the demand for transport? Will fossil fuel stakeholders respond to competition by increasing the fuel efficiency of vehicles and engines so the incentives for change are weakened? How effectively will the UK be able to compete in international markets for the technology and raw materials required for new energy systems?

### Advice to Developers

The future adoption of energy technologies is not a simple matter of technology but is also influenced by the economics of different power generation, delivery and storage systems, by their cultural acceptability and by the nature and scale of the energy demand within a society. Scenario developers should recognize the extent to which technologically plausible pathways into the future must also be consistent with their choices about social, economic and demographic pathways.

### Climate and Environment

The development of biofuels is often linked to concerns about climate change and questioned for its impact on the environment.

#### Climate

Climate change will ultimately affect both the supply of biomass for conversion to biofuels and the demand for fuel. However it is not likely to have a major impact by 2030: the IPCC projections show little divergence over this period between the possible global pathways to 2100 because the drivers for the next 20 years are already in the system. The issue for scenario authors is more one of the extent to which measures may have been taken by 2030 in the hope of managing the planet onto one of the lower increase pathways to 2100. Biofuels may make a contribution to reducing carbon emissions, although, at least for ethanol, studies show that this is not a large effect. Climate change is also likely to impact on the demand for energy, although not in ways that are specific to biofuels. Against the background of global warming, the UK is likely to experience more frequent extreme weather events - heatwaves in summer and cold spells in winter, although both will be buffered by the heat sink effect of the seas around the British Isles. The former will generate more demand for air conditioning and refrigeration, adding new summer energy demand peaks to established seasonal patterns. The latter will create spikes in demand in ways that are not qualitatively different from present-day cycles. Finally, climate change will have impacts on agriculture, affecting the opportunities for growing

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different crops, the distribution of plant and animal diseases and the resilience of subsistence farming communities.

### Advice to Developers

The main challenge by 2030, as noted above, is likely to be to the resilience and continuity of energy systems, if intermittent but renewable sources of supply become more important, which may have implications for the niche to be occupied by biofuels.

### Environment

Concern has been expressed about the environmental implications of biomass production. It should be stressed that these relate much more to the 'first-generation' approaches that rely on the production of crops specifically for biofuel production. Demand for these is, on the one hand, said to be crowding out food crops on prime agricultural land, leading to supply shortages within the global food market, and, on the other, to be driving the clearing and planting of 'marginal' land that may be agriculturally unproductive but which has other important ecosystem benefits. There is also evidence of impact on water supplies and water quality.

BBSRC's programme is concentrated on 'second' and 'third' generation biofuel production systems that do not compete so directly with food crops. However, they may still have adverse consequences if, for example, agricultural waste is used for fuel production rather than being ploughed back to maintain soil fertility. Against this, a common co-product of these biofuel production systems is high-protein animal feed, which may mean that less land need be devoted to meat production and that animal waste may be available as a fertiliser, possibly following its further use in biogas production. Some of these systems depend on non-food crops that may still consume marginal land: although native species, they could be modified by conventional plant breeding or GM techniques and grown as monocultures rather than as part of a diverse ecology. On the other hand, some also revive older agricultural practices, such as the coppicing of willow, which could make an important contribution to habitat restoration for particular wildlife species.

### Advice to Developers

In practice, first, second and third generation biofuel technologies are still likely to co-exist in 2030 and the main issue for a scenario is their mix within a scale of production determined by the assumed place of biofuels in the overall energy market. The larger this share, the more likely it is that later generations of biofuel are contributing, simply

because of the competition for land between food and fuel production where global population is continuing to expand. Evidence to date suggests that this is will be accompanied by demand for increased amounts of dairy products and animal protein, intensifying the pressure on land use because this is a less efficient use of land than in the production of cereals and pulses for human consumption. Climate change and desertification may also be having some impact by 2030, although this is not likely to be directly experienced in Northern Europe. Theoretically, of course, there could also be win-win outcomes where crops tolerant of desertification can be used for biomass, generating environmental improvement and new sources of income in some of the poorest countries.

### Social, Economic and Demographic

The socio-economic dimensions are crucial because technology does not determine its own progress and adoption. The choice of technologies, the speed of development and the nature of applications reflect a set of social and economic decisions about where to invest resources, based on both rate of return and societal values, how to absorb the results into existing patterns of social and industrial organization, particularly where they threaten to disrupt existing interests and institutions, and how to distribute the costs and benefits. We might, for example, consider the place of any particular nation within a global economy. Is it more profitable for a developing country to grow biomass for world energy markets than to grow food for domestic consumption? Do the terms of trade permit a country to specialize in energy crops and import sufficient food to compensate for loss of human foodstuff production? Are the incomes from energy crops monopolized by a few large-scale producers alongside displaced subsistence farmers or can this be managed by establishing co-operative production systems or encouraging new sources of market employment for displaced agriculturalists or facilitating migration to other sources of economic opportunity?

Social scientists typically deal with problems of complexity by focussing on one major variable and seeing everything else as secondary: economists think everything is to do with the allocation of scarce resources; geographers, the allocation of space; anthropologists, with culture and values; psychologists with personality, attitudes and cognition, etc. However, this specialization is a handicap in constructing and discussing scenarios because these need to capture systems as a whole rather than emphasising one dimension over another. At the same time, some simplification is

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essential if any progress is to be made in thinking with scenarios in the context of dialogue and engagement. We cannot have a scenario of everything – but we need a scenario that contains enough to be realistic. We have selected four dimensions that seem to us to be essential components of any scenario, particularly as they are likely to influence the market for biofuels: Economy; Demography; Location; and Culture.

### **Economy**

Economic activity is one of the major drivers for energy demand. Other things being equal, an active economy will use more energy for manufacturing, transport and domestic purposes than will a stagnant one. Factories operate for longer periods at higher levels of production, while citizens travel more for both business and leisure and use more energy for domestic amenity. The present context is one of great uncertainty about the likely course of economic activity during the next five to ten years, which will, in turn, frame the possibilities through to 2030. Scenarios need to reflect this. Some economists argue that deep and rapid cuts in public spending will lead to a short hiccup in economic growth which will then pick up on a more dynamic course led by the private sector. This may lead to some delays in energy investments but will not fundamentally constrain developments over the next twenty years. Other economists argue that these cuts will check growth to such an extent that the UK will slide into a period of stagnation comparable with that of Japan in the 1990s. This could mean a ‘lost decade’ of investment that would lead to a significant infrastructure and skills gap by 2030.

The prospects for the UK economy are closely linked to those of the global economy, particularly our major trading partners in Europe and the so-called BRIC (Brazil, Russia, India, China) countries with their rapid rate of development. Faster growth elsewhere could aggravate the UK’s problems by draining the bioenergy sector of skills and capital or it could create an expanding private market that facilitates export-led growth, producing a revenue stream for further investment, and retaining skills in the country.

### **Advice to Developers**

At this point, it is not possible to take a view on which pathway is more likely: scenario exercises should incorporate both low and high growth alternatives in an even-handed fashion.

### **Demography**

Energy demand will also be affected by the size and structure of the UK population – the number of potential

energy users, which is not wholly independent of either the economic or the climate change dimensions. The most recent (mid-2009) estimates from the Office for National Statistics suggest that the UK population is currently 61.8 million. By 2030, it is likely to lie somewhere within a range from 67 to 75 million. During this period, the population will also age, with about 23 per cent being over 65 by 2033 compared with 16 per cent in 2008. Population growth reflects an interaction between the number of live births, itself influenced by the number of women of reproductive age and their intentions, the number of deaths, influenced by environment, lifestyle and medical care, and net migration, the balance between inflow and outflow. On a low economic growth pathway, population is likely to grow more slowly: women have fewer children, mortality rates decline more slowly and net migration tends to be small or even negative. On a high growth pathway, the converse is likely to be true. Scenarios which select low economic growth pathways would most plausibly be associated with lower expectations about population growth, and vice versa. In either case, though, the ageing of the population should be assumed to be given, since the people who will be over 65 in 2033 are alive today and are still likely to be alive then.

However, scenario developers should take account of the possible complications of global factors. If climate change accelerates, the UK may become a more favoured destination for migrants regardless of its own economic performance, although this is unlikely to have a strong impact by 2030. The issue is one of relative economic performance: adverse effects on other countries, particularly in Africa, may push their citizens and residents towards migration. By 2030, this may be an increasing pressure on the EU as a whole, rather than the UK in particular, but some climate projections suggest that parts of Southern Europe may not be sustainable places to live by the end of the century. If so, we may see migration pressure from these zones on more northerly parts of the EU. Within a range of plausible scenarios, particularly looking beyond 2030, we could imagine a flat UK economy with more substantial population growth from climate refugees, depending upon EU and UK immigration policy. While this may not be a strong candidate for debate over pathways to 2030, it nicely illustrates the way demography and economy interact with culture and the value placed on free movements across national borders.

As noted above, all scenarios must consider the implications of an ageing population. Current projections suggest that the number of households is likely to grow by 29 per cent

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between 2006 and 2031, with two-thirds of the increase accounted for by single-person households, particularly among older people. An increased number of households implies an increase in domestic energy demand simply because heating, cooking, and transport requirements do not decline proportionately to the number of people in a household. Older people may actually have greater requirements for heating, particularly if they are at home much of the day, although low economic growth could lead to fuel poverty, where older people cannot afford as much energy as they would like or as might be optimal for their health. We can also infer that there is likely to be increased transport demand from carers, whether kin or paid. Care services going to old people living alone will generate fuel demands, as, potentially, will journeys by kin to sustain relationships or to cover for limitations in public or private care services, or in access to them, which may also be aggravated by low economic growth. This will probably impact on the demand for migrant workers because the ratio between the working age and the pensionable population is projected to fall from 3.2 to 2.8 between 2008 and 2033. Working adults cannot simultaneously be employed in producing tradable goods and services and in care work, whether paid or unpaid. The paid care sector already depends heavily on migrant labour and this seems unlikely to change, unless there are major shifts in immigration policy and in the home population's employment preferences.

Migration will also affect international transport demand. Inward migrants often wish to retain contact with their countries of origin. Outward migrants may wish to sustain links with their families and professional associates that are of value to the UK. However, the issue is less one of the net balance between inward and outward migration than of the overall volume and whether it is primarily within the EU or involves longer distance movements. If migration flows are primarily within Europe, there could be some substitution of surface for air travel, which would have implications for the balance of demand between liquid biofuels suitable for aviation use and biofuels suitable for electricity generation, powering long-distance rail services, or for long-distance road transport, which is unlikely to be provided by current battery technologies. Shorter term movements should also be acknowledged. Through to 2030, there are unlikely to be major shifts in tourism patterns within Europe. Over a longer period, however, hotter summers and desertification in traditional Mediterranean destinations may make the UK an increasingly attractive holiday destination because of its more equable climate.

### Advice to Developers

Scenario exercises need to be able to reflect both high and low UK population estimates and high and low rates of mobility. However, the ageing of the population should be treated as a constant feature under any scenario, together with its implications for household size.

### Location

UK land use planning has generally produced higher residential densities, and less suburban sprawl, than in North America or Australia, facilitating the sustainable use of urban public transport. There has, however, been difficulty in containing long-distance commuting from rural areas and market towns into cities, particularly in the South East. While there has been some re-population of central London, in contrast to the continuing declines experienced by many industrial cities, the most rapid population growth has occurred in areas like Northamptonshire and Oxfordshire, where it is difficult to design public transport alternatives for many commuting journeys, and where those journeys may be too long for battery-powered cars. Although teleworking has long been seen as a magic solution to this problem, it has failed to take off on any scale sufficient to have an impact. Indeed, it may even be increasing travel demand by facilitating working from many places 'on the move' rather than from a home base. This may be offset by reductions in workplace energy demand, but these could be outweighed by home-based workers' extra domestic energy consumption. There are many unanswered questions about the overall impact of remote working and scenarios should not assume it will be a major factor through to 2030.

Internal migration may be more important. Economic opportunities are unevenly distributed within the UK and this is unlikely to change within either the high-growth or low-growth economic pathways. This generates transport demand, towards areas offering employment opportunities and in return to maintain family and other networks. While this may be manageable, in energy terms, by greater use of electrified rail services between major cities, the perceived affordability of this mode relative to private car use or long-distance buses may affect the balance between fuels for power generation and liquid fuels for transport purposes.

### Advice to Developers

Overall, it would be unwise for scenarios to assume that changes in where people live are likely to exert much influence on demand for biofuels, relative to other socio-economic factors. The important conclusion is that there is likely to be some continuing level of demand for liquid

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biofuels for transport markets that cannot be converted to other sources.

### **Culture and Values**

One of the hardest areas to incorporate in scenario design is any presumed shift in societal values over a relatively short period. There are many opportunities for wishful thinking and simplistic assumptions about the degree to which citizens will in fact voluntarily modify their behaviour to fit the assumptions of planners or lobbyists, whether on behalf of industry or Green NGOs.

Some scenarios might be based on a 'Deep-Green' Utopia of a planet with 2 billion or fewer inhabitants – against the 7 billion or so today and the 9 billion projected for 2050. However, caution should be used in treating this as a plausible direction of travel by 2030, rather than as a way to explore reactions to the implications of such a way of life. Advocates of these outcomes tend to depict a world dominated by communitarian values, which favour village-scale communities, depending largely on their own local resources, with very limited travel and trading between them. Bioenergy may have a part to play in this sort of socio-economic system, but it is unlikely to require the technical complexity assumed by BBSRC investment. The main biofuels would have to come from coppicing and plant waste with little or no intermediate processing. In fact, it is not clear how this vision would sustain any level of technological complexity as in contemporary biofuels – and indeed wind or solar generation - because of the scale of trading and production networks involved. A community might build a windmill or a water wheel from local resources but it is improbable that either could reach the sophistication and efficiency of a contemporary wind- or water-turbine. It should also be noted that this vision does not have strong roots in any actual historical society. Recent discoveries at Stonehenge, for example, have shown a surprising and unexpected degree of mobility as long ago as the Neolithic period, with the remains of humans from the Mediterranean being found in graves in Wiltshire. Internal UK migration towards greater economic opportunities in the south and southeast of the country can be documented at least as far back as the thirteenth century.

Scenarios should, then, also recognize and give equal weight to an alternative utopia where markets are allowed free play to allocate resources. In theory, their advocates argue, properly functioning markets will send signals to consumers through the price mechanism that will influence their purchasing decisions in an environmentally sensitive

fashion. In practice, of course, the outcomes may be different, not least because of the difficulty of capturing the present costs of distant future possibilities in current prices. Uncertainty over the drivers of climate change and its likely costs by 2100 makes it hard to set a price for carbon-generating energy supplies in 2030. Moreover, affluent citizens may simply decide to pay a higher price rather than change their behaviour. If I do not wish to experience the common herd on public transport, I can continue to drive my SUV and park it at will, simply by making a marginal reduction in my discretionary spending on something else. Markets are also seen as more powerful drivers of innovation both to maximize those 'goods' sought by market actors and to minimize the 'bads' that they wish to avoid. The communitarian vision often has a very static quality as if nothing would ever change and nothing new would ever happen.

### **Advice to Developers**

The choice between a communitarian or a market future reflects prior ideas about what constitutes a good society, what level of material comfort is appropriate and what degree of personal autonomy is desirable. In reality, the future, like the present, is likely to contain elements of both, but the use of pure types in scenario exercises may help to focus dialogue and engagement on the acceptable range of compromise. The important thing for scenario developers is to present groups with examples of both in an even-handed manner.

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## Chapter 2 Scenario Examples and Their Use

This chapter presents four examples of how scenarios for bioenergy futures could be developed and discusses their use in public engagement work. Some users may wish to take these over directly, but we hope that most will see what we are doing as modelling a process that can be used in ways that reflect the interests of different audiences, the background of the facilitator and the issues that she or he is interested in exploring.

One of the particular challenges for users is likely to be keeping groups focussed on the topic of bioenergy. In part, this reflects our attempt to develop more realistic scenarios that place biofuels within a context of competing energy sources and potential social, economic and cultural changes through to 2030. When seen in that context, biofuels may not be the most important development from the group's perspective. There is nothing wrong with this as a corrective to narrow single-issue public engagement exercises that can get the specific issue out of proportion. At the same time, the object of this public engagement programme would be defeated if there were no relevant feedback for BBSRC and other stakeholders because participants became so interested in other elements of the scenarios.

This risk may be aggravated by our attempts, within the limits of public funding, to produce materials that will provoke reactions. As we said earlier, scenarios are not predictions but possibilities that are designed to stimulate debate over potential pathways into the future and what this might imply for choices in the present that will constrain those options. While the scenarios are constrained by current projections and models or by ideas that have already been canvassed, the narratives deliberately take a more dramatic form in order to generate audience reaction. As a user, you may feel this is overdone, although you may then find some groups are less challenged and therefore less responsive in discussion. Alternatively, you may feel that some could actually be made more provocative – we do not, for example, offer much of a 'virtual history' of the economic and policy developments that create these different images of 2030, although this might stir up more debate. Going down this route, though, could lead a group into political discussions at the expense of considering energy policies. While these ultimately involve political choices, those choices are not necessarily highly partisan in relation to technologies.

Each narrative is prefaced by a scenario of assumptions that have been used to create the conditions portrayed and is followed by suggestions about how it might be adapted,

developed and used in public engagement work, particularly in activities with a variety of different groups.

### Scenario 1: No Change of Course

This scenario represents the middle box of the matrix, where there is some biotechnological progress within a broadly neutral context.

#### Scenario components

**Technology: Improvements in the microbial breakdown of lignocellulose as a source of biomass for ethanol and the expanded production of biodiesel from catering and similar waste plant oils.**

The genetic engineering of microbes and developments in enzyme chemistry make it possible for a greater variety of biomass feedstocks to be used in ethanol production, particularly from plant stem waste and from crops like perennial grasses and coppiced trees. However, continuing public resistance to GM technology means that this has not been used to accelerate feedstock growth but only in the closed environments of biomass conversion. Ethanol is added in limited amounts to petrol for motor vehicles but the problems of corrosion and water attraction mean that it is only used as an exclusive fuel in a few applications like buses, where the relatively high initial investment and specialized fuel supply chain mean that the cost of using resistant materials and technologies in engines and fuel tanks is marginal and can be recovered over the lifetime of the vehicle or its support facilities. Market incentives – rising hydrocarbon costs and waste disposal fees – have encouraged an industry in the collection and refining of waste vegetable oils, which has seen evolutionary improvements from the use of microbial rather than chemical agents in the reprocessing. There is growing optimism that the limited supplies of vegetable oils can be supplemented by the use of algae or yeast as the initial biomass, removing the need for plant-sourced feedstocks, although there is some concern that this might present a problem in dealing with the vegetable oils, which will still be required in other applications.

#### Context

**Competing Energy Technologies: Biofuels make a contribution to a diverse market**

Continuing increases in the efficiency with which traditional hydrocarbon fuels are used have limited the adoption of alternatives. Vehicle users and private households have responded to rising energy costs by demanding more

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efficient engines in private cars and light vans and by improving the insulation of their homes. There has been some movement away from natural gas as a fuel because of supply uncertainties and a policy goal of diversifying supply, which has resulted in subsidies to expand both nuclear and renewable sources. Electric vehicle use has increased among residents and traders in larger towns and cities, where journeys are relatively short and some pooling is possible among residents in high-density neighbourhoods. One showpiece high-speed rail line has been opened from London to Birmingham but funds have not been available to extend this. Within this market, biofuels are used mainly as an additive to hydrocarbon fuels in most transport applications, diluting diesel, aviation kerosene and petrol by up to 20 per cent but only displacing them in a few areas like urban bus fuel, where specialist engines and supply chains have contained the technical problems of ethanol use. There has been some small-scale adoption of biomass for electricity generation, mainly from renewable planting, particularly willow coppicing, in areas that are too remote for mains electricity connection. Similarly, biomass feedstocks are beginning to displace hydrocarbons in some industrial applications, particularly where the industry is concerned to manage its public image as responsive to environmental and climate change issues.

## **Climate and Environment**

### **Climate: Neutral**

Although climate change continues to be a matter of social and political concern, the containment of demand by responses to changing prices and the substitution of renewable or nuclear sources for some gas-powered electricity generation has lessened the perceived urgency of the challenge for the UK. The country is projecting a slow decline in carbon emissions, although remaining above the levels that some climate scientist regard as optimal. However, a lack of action elsewhere, particularly in the US, means that it is difficult to argue for more vigorous interventions. Global warming is following a low to median track in the IPCC estimates and is seen as a problem manageable by further technological development rather than major social or economic changes. As a result, the new technology has largely been grafted onto an existing way of life.

### **Environment: Neutral**

Climate change has had some impact on marginal subsistence agriculture, particularly in Africa and parts of Central Asia, producing localized problems of population movement. It has also made some traditional Southern European holiday destinations uncomfortably hot during

the summer months. Despite the developments in second and third generation technologies, previous investments in first-generation technologies continue to generate biomass demands that provoke competition for land use between energy and food crops. Advances in plant breeding mean that it is still not clear whether the consequences are higher food prices and occasional shortages or whether these are due to the continuing lags between population growth and agricultural development in specific global regions.

## **Socio-Economic**

### **Economic: Medium-growth**

The UK economy has recovered from the 2008 economic crisis but resumed its historical path of somewhat slower growth than that of other European countries. As a result, UK living standards have not fully kept pace with those of Germany, France and the Nordic countries, all of whom have had greater resources to invest in infrastructure development, albeit often financed by British capital. This economic pathway has left a continuing problem of unemployment in some regions of the UK, particularly among younger and less-skilled workers.

### **Demographic: Medium-growth**

The lagging economy has reduced the demand for labour, with inward and outward migration, mainly among the 20-35 year old age groups, more or less in balance. Although immigration controls have been extended, there has been limited pressure, although some other European countries are struggling to contain climate-induced migration from Africa and Central Asia. The ratio of the working age to the retired population continues to decline, although this has been countered to some extent by rises in the retirement age.

### **Location: Neutral**

London continues to have a stronger demand for labour than most of the rest of the UK and to draw young people from the provinces to meet this. As a result, there continues to be pressure at all levels of the housing market in that area, although demand is relatively weak elsewhere and met largely by refurbishment of existing properties rather than by new construction.

### **Culture and Values: Generally pro-market**

At least since the 13th century, the English have tended to have a more individualist approach to life than their European neighbours, with occasional brief interruptions. The political culture continues to emphasise market-oriented values and to design social institutions around these.

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## Everyday Life in 2030: Alex Palmer and his friends

Alex Palmer's alarm goes off at 06:30 on a damp Monday morning in Stratford, East London. He rubs the sleep from his eyes – last night was a late return from a heavy weekend in Berlin, thanks to the European high-speed rail network. Next weekend he thinks he must go home and visit the family in Nottingham but that would take as long as going to Brussels and cost about the same. Life brings hard choices sometimes. He hears one of his flatmates stirring and decides to head for the shower. The pressure-restricting valves that have been retrofitted reduce the flow to a bare trickle but the water is reasonably hot and he can get through without irritating his flatmates by his energy consumption – Marcus had been asked to leave three months ago because he liked lengthy showers and the monthly bills had gone down by ten percent immediately.

The kitchen is as scruffy as those of most young flat-sharers. He picks a cleanish-looking mug and fills it with cold water to measure into the kettle. Another of Marcus's sins was running in too much water so there was no risk of ending up with the crunchy bits of scale that London supplies always leave in the bottom of a kettle. While waiting for the water to boil, Alex rubs at the edge of the dent in the thermal plasterboard where someone had danced with a saucepan on their head at the last party. The apartments had been hurriedly built for the 2012 Olympic Games and the quality of finish had never been outstanding even before the landlord had tried to do an internal upgrade on their insulation. Alex yawns again and thinks of his weekend. The club where he had been on Saturday night was powered by an energy recovery floor so every dancer did their bit for the light and sound system. Sometime around 03:00 he had gone home with a guy who had been selling coke at the club. Daybreak showed solar panels on every roof and the dealer had told him that the city government was planning to install energy recovery paving throughout the central pedestrian zone. Because the Germans did not want to build nuclear plants, pretty much all domestic and social energy use was now derived from renewable sources, reserving hydrocarbon fuels for industrial and back-up purposes. The increased integration of the transport system between rail, tram and electric taxis meant that few people really needed private cars.

After coffee and an oat crunch cereal – maize-based breakfast cereals were rather expensive at present because of supply shortages – Alex walks down five floors to the pool car park under the building. He could have used the lift but the landlord has installed a smart card meter to charge users for the energy costs and he doesn't have luggage to carry today. Two other young people are waiting for him. They all work at Thames Gateway Nine, one of the satellite hubs where poorer people have been rehoused because they cannot compete in the unsubsidized central London housing market. Alex works for a job-placement company, under contract to the social security fund that tries to find work for people. His colleagues, Cindy and Bethan, work for a related company that promotes co-operative workshops in bioenergy services, providing working capital and business advice. They peer round the electric cars in the pool, looking for one that is not full of empty crisp packets and soft drink bottles. In theory users are supposed to remove their rubbish to the recycling bins at the end of the parking area but no-one ever bothers. Eventually, they choose one and Alex swipes his card to rent it.

As they pull out of the car park, one of the capital's fleet of ethanol buses eases into the stop on the other side of the road. These buses are now running on algae-derived ethanol with a smell that has led Londoners to nickname them after a former Mayor whose love of his own voice was equated with flatulence. There are a few diesel buses left in the outer suburbs but they all use a biofuel mix, derived from the capital's plentiful supply of waste cooking-oil. Alex and his friends follow the Gateway Spine road. The various hubs along the estuary are separated by willow plantations, although the marshy Essex land has proved to be too contaminated for them to grow as well as predicted and public resistance has blocked the introduction of more tolerant GM varieties. The willows have yielded some biomass for the biorefinery and mixing plant at Canvey Island but the real energy supply can be seen in the turbines out in the estuary and the distant nuclear station at Sheerness.

Thames Gateway Nine is a pleasant mixture of office park and low-rent shopping mall, surrounded by native trees and water features that drain the marshland on which it is built. The German-built solar panels on the roof and the high insulation standards meet most of the users' needs. As Alex drives into the staff parking area and hooks up the charging cable on the car, his boss, Anwar Patel, gets

out of his Swedish-built car. Like many of the people who have made money in contracted-out services, he chooses to live in the opposite direction, in an executive village on the Essex/Suffolk border, threading his way across the main East-West commuter axis to Gateway Nine. The car runs on biodiesel, imported in liquid form from countries with more successful systems for collecting and processing mixed urban waste, using Finnish microbial technology.

Alex's clients mostly live in low-rise terraces radiating out from the centre. These are already looking fairly dilapidated because the poverty of the occupiers means that their rent payments are too low for the landlords to fund routine maintenance and make a return on their investments. For the same reason, there is little public transport, although most live within about thirty minutes walk from the Hub. Employment is difficult out here

because travel costs to low-wage jobs tend to make them uneconomic. Some large residential and nursing homes were established to use the cheap labour but they have proved unpopular workplaces and Alex often finds himself in a revolving door, placing people who contrive to lose their jobs as soon as they have re-established their social security rights. There used to be a bioplastic factory, built to use the willow crop which was never sufficient to sustain it. Eventually it was relocated to Lithuania, where people were more accepting of fast-growing GM tree plantations.

Alex calls for his first client of the day. While he waits he stares again at the poster on the wall – a large tree with the caption “from tiny acorns grow mighty oaks”. It might be supposed to inspire the clients, but this morning is definitely one for acorns rather than oaks...

## Using the Scenario

The choice of actions here will reflect your assessment of the groups involved. Some may prefer to concentrate on the assumptions and to think about how varying these might affect the picture of everyday life, while others prefer to focus on thinking about the story and what would have to be different for this to change.

- **Vary the technology.** Suppose there had been greater public acceptance of GM willow, for example, so that local supplies of biomass were more plentiful? Would this make a difference to the potential for biofuels or bioplastics? The scenario assumes developments in ethanol technology. What if the big improvement is in microbes delivering butanol which has fewer technological problems and greater octane potential than ethanol? Would this make it a more genuine competitor as a fuel for private cars? Would that affect the likelihood of car pooling taking off?

- **Vary the context.** Would the future look very different if biofuels had come to market before large investments in nuclear power and offshore renewables? Why is it only the new office building that is benefitting from solar panels? The reference to the price of maize breakfast cereals suggests that there are problems from international competition for food supplies. Could the UK do anything to reduce this? What would the consequences be for countries from which we import food or biomass? This might also be a place to discuss the way that values have shaped the future. Does the continuing failure to adopt GM technology reflect a lack of scientific understanding or a value choice to prefer the

purity of our vegetation over a reduction in our share of the demand for biomass from other countries? What about the conflict within Alex's flat over Marcus's energy use? Is there something here about different values and the impact of energy pricing on behaviour?

- **Vary the narrative.** How would other people in this scenario describe their lives? Could a group develop narratives of what life would look like for each of them under the scenario assumptions? Alex Palmer is presented as a young, single flatsharer, perhaps easy for student and even school groups to identify with. Some people might not feel comfortable with a gay central character, although others will appreciate being reminded that energy issues affect everyone. Facilitators could easily rewrite the story around a straight character, if they thought this would work better with the group. Alex has parents living in the East Midlands, a relatively poor area of the UK. If you were working with a community group of people in middle age or older, they might identify more with Alex's parents. What would their lives be like? Other groups could identify more with Alex's clients. What does the scenario mean for them? How could you incorporate their stories? Are there sections of the population that are doing well under this scenario? Who might they be? Could you look at this from the point of view of Alex's boss, Anwar, with his executive home and his Swedish car? What might his life look like? What does this mean for energy demand in general and the place of bioenergy within that mix? You might split a group into smaller units to work on different aspects and then bring them together to produce a shared story.

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As with all the scenarios, there are various ways in which you could encourage a group to express their thinking and responses. Some groups might write their own stories but you could also use pictures or short video presentations. Could you draw pictures of Alex Palmer and his friends in their homes and workplaces? Could you produce a regional TV news bulletin about the closing of the bioplastics factory, building on the scenario assumptions and the implied environment in the everyday narrative? This might, for example, investigate the problems in supplying biomass from the willow plantations and the alternative uses in the Canvey Island biorefinery. Perhaps a group could develop a short play around Alex interviewing some of his job-placement clients or around Bethan and Cindy's efforts to promote start-up co-operatives in bioenergy services.

Once a group has explored the issues, you can ask them for an evaluation. Do they think this is a gloomy picture or is it a future they could live with? How did it come about? What would policy makers and other citizens have to do to create a future that was more attractive to the group members? How would biofuels play a part within that?

## Scenario 2: Bumping along the bottom

This scenario represents the bottom left of the matrix, where there is marked biotechnological progress but an unfavourable context.

### Scenario components

#### Technology: Biodiesel produced from biological wastes and refined into aviation-grade biokerosene.

There is an important breakthrough in engineering *S. cerevisiae* to convert human and animal waste into isoprenoids that can be processed into high-quality aviation fuel at a price below that of conventional oil products and with a higher energy content so that it is both cheaper and weight-for-weight more efficient. Although this fuel has comparable carbon emissions to those of conventional oil products, its greater efficiency means that less carbon is emitted on any particular flight. This fuel is mostly produced in large population centres where huge volumes of human and animal waste can be relied upon as a stable source of feedstock and distributed through the oil companies' traditional networks.

### Context

#### Competing Energy Technologies: Biofuels have a niche market

Improvements in solar power capture through large-scale arrays in desert areas have created massive supplies of low-

cost electricity, which can be used for most transport and heating purposes, either directly or through high-efficiency batteries. Hydrocarbons are still used extensively as chemical feedstocks. Apart from aviation, biodiesel from biowaste has a niche market in long-distance freight and off-road transport use, such as agriculture, mining and construction. There has been some small-scale adoption of biomass for electricity generation, mainly from renewable planting, particularly willow coppicing, in areas that are too remote for mains electricity connection.

### Climate and Environment

#### Climate: Neutral

Although climate change continues to be a matter of social and political concern, the rapid development and adoption of low or zero carbon energy technologies has lessened the perceived urgency of the challenge. Global warming is following a low track in the IPCC estimates and is seen as a problem manageable by further technological development rather than major social or economic changes. As a result, the new technology has largely been grafted onto an existing way of life.

#### Environment: Neutral

Climate change has had some impact on marginal subsistence agriculture, particularly in Africa and parts of Central Asia, producing localized problems of population movement. It has also made some traditional Southern European holiday destinations uncomfortably hot during the summer months. However, the emphasis on solar sources within the energy mix means that there is limited competition between food crops and biomass, particularly as second- and third-generation biofuels have tended to use waste materials.

### Socio-Economic

#### Economic: Low-growth

The UK economy has historically grown more slowly than that of other European countries. It was slow to recover from the 2008 economic crisis and growth has averaged 1.5% per annum ever since, whereas that of Germany has been 2.1% and of Poland 3.5%. As a result, UK living standards have declined relative to the rest of the EU and there are continuing high rates of unemployment, particularly among young people.

#### Demographic: Low-growth

The flat economy has led to a decline in inward migration, because of low demand for labour, and an increase in outward migration, in search of employment, both

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predominantly affecting the 20-35 year old age-groups. As a result the birth-rate has also declined, because those groups are having their babies elsewhere in Europe. This has also led the ratio of working-age to retired population to deteriorate faster than predicted.

#### Location: Neutral

The lack of economic growth means that there are few changes in where people live or move to. London continues to have a stronger demand for labour than most of the rest of the UK and to draw young people from the provinces

to meet this, particularly since other young Europeans are being attracted to more dynamic parts of the EU, which are creating more opportunities for skilled workers and professionals.

#### Culture and Values: Generally pro-market

At least since the 13th century, the English have tended to have a more individualist approach to life than their European neighbours, with occasional brief interruptions. The political culture continues to emphasise market-oriented values and to design social institutions around these.

### Everyday Life in 2030: Mrs Palmer goes to work

It is 04:00 and Mrs Palmer is setting out from her home in Nottingham for her work as a cleaner at East Midlands airport. Her husband, a joiner, is working away as a labourer on a new science park being constructed outside Krakow in Poland – his skills are not considered sufficient to work at his trade in that country but the lack of construction work in the UK has exhausted his lifetime cap on unemployment benefits and the family need his remittances. Their 14-year old daughter is still at school, although she works an unpaid three-hour shift most days in a care home under the national community service plan. They also have a 22 year old son who attended the local vocational university and is now living in a dormitory block in London where he is doing the year's unpaid work that is required prior to participation in the lottery for public sector employment opportunities. He studied accountancy and hopes to work in tax collection so he can acquire skills that will make him employable in the private sector. Major accountancy firms now mostly recruit from outside the UK except for a small number of international elite universities, because low economic growth has led to a lack of investment and the emigration of many academics. He could have attended one of these but was reluctant to incur the level of debt involved especially since the Employment Promotion Act 2025 had allowed firms to dismiss all workers with 28 days' notice and removed statutory levels of redundancy pay.

The Palmers' home is heated and lit by electricity. It had benefitted from the big retrofitting drive to insulate housing following the fuel shortages of 2020-2022 when the lack of investment in new power stations and the failure of others run beyond their design life had led to repeated winter disconnections during which several

hundred people had frozen to death in their own homes. However, the family struggled to meet the energy bills because the then UK government had refused to participate in the EU Sahara Sunshine solar project that brought cheap and abundant energy to most of mainland Europe, arguing that this should be financed solely from private sources. The European power companies that had promoted the development with public investment support from their home governments via the EU saw the unregulated UK market as a way to absorb marginal capacity and make higher returns than they were allowed to do in their own countries. The streets along which Mrs Palmer walks to the bus are also lit by electricity, although only one street lamp in three works, following the squeeze on local government in the 2025 programme of deficit reductions in a further attempt to balance the national budget. Mrs Palmer's bus is an electric vehicle of older design – it was bought second hand from Hungary. It is prone to regular failures and the battery discharge rate is erratic leading to sudden bursts of acceleration and deceleration that are hazardous to other road users. There are a few biodiesel buses but these are mostly to be found in rural areas in Wales and Scotland where the transmission lines are not adequate for charging the size of batteries needed for buses and the devolved administrations are more willing to offer subsidies to operators who need to use a liquid fuel.

When Mrs Palmer arrives at the airport, she greets her co-workers, many of whom are older than she is and employed under the Contribute to the Community scheme, where employers are exempted from national insurance contributions when employing older workers part-time, if the workers' only income would otherwise be a state pension. The airport used to be busy with holiday, budget and airfreight traffic. Much of the holiday and

budget traffic has now gone because UK residents cannot afford the travel, European immigrants have returned home or moved to more prosperous parts of the continent and European holidaymakers looking for relief from the baking heat of the Mediterranean have found East Coast resorts like Skegness to be inaccessible and unattractive compared with those on the Atlantic coasts of France and Spain. Business traffic has increased with the deterioration of the UK road and rail infrastructure and the airfreight is booming as high value goods come in for sorting and distribution by air across Northern Europe, attracted by the region's cheap land and labour for freight handling work.

Before their shift starts, the workgroup check out the ready meals in the vending machines that have replaced their canteen. Few of these now contain any meat products because of the UK's inability to compete for high-value food supplies in world markets. Most are built around vegetable protein engineered from biofuel co-products. This used to be fed to animals but has been modified to make it more palatable to humans.

Mrs Palmer sniffs the characteristic smell of jet biofuel as she starts to wipe down the windows of the apron supervisor's office – funny the way they engineered it to smell like roses when you think how it started out...

## Using the Scenario

The choice of actions here will reflect your assessment of the groups involved. Some may prefer to concentrate on the assumptions and to think about how varying these might affect the picture of everyday life, while others prefer to focus on thinking about the story and what would have to be different for this to change.

• **Vary the technology.** Suppose the development had been in motor vehicle technology to use ethanol, for example, so that there was more demand for biomass from crop plants and more emphasis on liquid fuels than on electric power. Would this make a difference? Consider comparing crop plants grown on land that threatened with desertification with crop plants grown on land that would otherwise be used for food crops – remember that converting land from food to fuel crops is not necessarily bad for a farmer, even at subsistence level, if this generates a cash income sufficient to buy the food from someone else whose land may be less adaptable.

• **Vary the context.** Would the future look very different if biofuels had come to market before long-distance solar power? What are the security implications of relying on desert states for energy, although these may include parts of Spain, Greece Italy and France by 2030? What happens at night – what keeps the lights on? How sensitive is the scenario to the assumptions about relative economic growth? Suppose the UK could afford more investment in new energy sources – would the group go for biofuels? Why?

• **Vary the narrative.** How would other family members describe their lives? Mrs Palmer has a family. Could a group develop narratives of what life would look like for each of

them under the scenario assumptions? If you were working with a school or college-age group, could they develop narratives from the point of view of her son and daughter? Could some groups relate better to the experience of her husband? Mrs Palmer is positioned in the East Midlands, a relatively poor area of the UK. Would the picture look very different if she lived in London? Would life under a devolved administration within the UK look better or worse? How would things look to the apron supervisor or the chief executive at the airport? Are there sections of the population that are doing well under this scenario? Who might they be? What does this mean for energy demand in general and the place of bioenergy within that mix? You might split a group into smaller units to work on different aspects and then bring them together to produce a shared story.

As with all the scenarios, there are various ways in which you could encourage a group to express their thinking and responses. Some groups might write their own stories but you could also use pictures or short video presentations. Could you draw pictures of Mrs Palmer and her family in their various workplaces? Could you produce a regional TV news bulletin about typical events, building on the scenario assumptions and the implied environment in the everyday narrative? How might this family's life be reported in a feature for the 2030 equivalent of a broadsheet weekend colour magazine? What would a feature on bioenergy generation in the same magazine look like – is it good news or bad news? How would the same story be covered in, say, a West African or an Indian news medium?

Once a group has explored the issues, you can ask them for an evaluation. Do they think this is a gloomy picture or is it

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a future they could live with? How did it come about? What would policy makers and other citizens have to do to create a future that was more attractive to the group members? How would biofuels play a part within that?

### Scenario 3 How Green is my Valley?

This represents the middle-right box on the matrix, where biofuel technologies make modest progress in an otherwise apparently favourable environment. This scenario particularly stresses value changes in a communitarian direction in order to provide an opportunity for group participants to explore what these might mean for everyday living. As such, it tends towards a 'Deep Green' approach that has relatively few contemporary advocates but which allows a facilitator to ask exactly how far participants would be willing to go in adopting the values and lifestyle presented here. Remember that these scenarios are not predictions but tools to generate debate.

#### Scenario components

**Technology: Butanol produced from algal wastes after oil extraction. Timber biomass used for localized electricity generation**

A hyperactive strain of E.coli has been successfully engineered to produce butanol which can easily be used in existing petrol engines and blended with diesel at high levels. The microbes' feedstock is the fibrous residue after extracting oil from algae, creating a particularly efficient low-carbon process that can operate on a regional scale wherever there is an adequate supply of sunlight and nutrient-rich water sources. Indeed, some algae strains have also been developed that can clean up water contaminated by heavy metals, yielding small but recoverable quantities of these as well as biodiesel. However, although this technology is efficient in terms of production, it requires high initial levels of capital investment to construct the basic facility and to install continuous monitoring systems to ensure that both algae and microbes are maintained in optimum growing conditions and are not contaminated and out-competed by more vigorous wild strains. There are also developments in other forms of biomass, particularly in the growth of timber for wood-based electricity generation through genetic engineering of tree species for faster growth and suitability for coppicing. Timber biomass is carbon-neutral and can be used in microgeneration units to minimize emissions from transport but supplies are relatively finite because of land-use competition from food crop production intended to reduce import demand and

transportation by ship or plane, both of which still depend on hydrocarbon -based fuels and produce significant carbon emissions.

#### Context

**Competing Energy Technologies: Biofuels and local renewables dominate the market because energy demand is closely regulated to suppress competition and minimize usage.**

Regulatory interventions have massively reduced energy demand. Conventional hydrocarbon technologies survive in niche applications like aviation and shipping but an emphasis on local self-sufficiency and distributed or remote-access services has left little space for them in the energy mix. Large-scale renewables have not taken off because of the carbon costs of their initial construction and of the transportation of rare minerals involved in their manufacture.

#### Climate and Environment

**Climate: Neutral to favourable**

Increasing concerns about climate change, prompted by extreme weather events in the UK, have led to growing caution about any process that emits carbon - even if this is broadly neutral. Governments are trying to shift towards a negative emission position where carbon is being locked up faster than it is being emitted. Although both butanol and biodiesel can be produced on a regional scale, reducing emissions in the supply chain from fuel production to end-users, their carbon outputs are only about one-third lower than those of oil-based fuels and are still contributing to greenhouse gas generation.

**Environment: Neutral**

Climate change has had some impact on marginal subsistence agriculture, particularly in Africa and parts of Central Asia, producing localized problems of population movement. Aggressive energy demand management has limited competition between food crops and biomass, particularly as second- and third-generation biofuels have tended to use waste materials as feedstock. However, the depression of demand for biomass export crops has hit farm incomes in developing countries and aggravated problems of poverty and underinvestment.

#### Socio-Economic

**Economic: Low to medium-growth**

The UK economy makes weak growth recovering from the 2008 economic crisis and is left badly exposed to a

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further shock in 2018. (This might be caused by conflicting economic policies in the US and China in an attempt to remedy the trade imbalances between them or by a major default in a lightly regulated financial system like that in India. The precise cause does not matter since there are a number of plausible possibilities.) Given the recent memories of 2008, confidence in market economies is badly shaken and a greater degree of central planning has at least a short-term impact in promoting growth and rebalancing away from dependence on the UK financial sector.

### Demographic: Low-growth

The flat economy and discouragement of personal mobility has led to a general decline in all forms of migration, whether within the UK or internationally. The economic uncertainty and negative attitudes to reproduction as a personal choice with consequences for carbon emissions has led to a decline in the birth-rate. This has led the ratio of working-age to retired population to deteriorate faster than predicted.

### Location: Neutral to favourable

The flat economy and discouragement of personal mobility mean that there are few changes in where people live or move to.

### Culture and Values: Collectivist or communitarian

Although the English have tended to have a more individualist and pro-market approach to life than their European neighbours, they have been badly shocked by a further financial crisis and a succession of extreme weather events, accompanied by mortality surges among vulnerable groups who have been unable to meet the costs of adequate heating or cooling in their homes. As a result, there has been a reaction in favour of more collectivist and communitarian policy choices, much as happened in the 1940s in response to the economic troubles of the 1930s and the challenges of the Second World War. This includes the introduction of personal carbon credit quotas as proposed by a number of academics, politicians and environmental groups from about 2005 onwards.

### Everyday Life in 2030: Mr Patel and the Village Hub

It is a bright May morning as Anwar Patel unlocks the Village Hub and reviews his workplan for the day. This will begin with his weekly trip to the regional distribution centre on behalf of the village in the community van. He will restock the shelves of the shop area in the Hub and collect supplementary food orders, mail and parcels for the villagers. The van also has seating for four passengers where villagers have carbon credits that allow them to travel for socially authorized purposes. Sharing the van uses fewer credits than renting one of the village cars and is often necessary for villagers who have to make unexpected journeys. This week he will also need to refuel the van from the regional biofuel depot. He runs over the schedule on his smart tablet. Cindy and Kate, the online credit controllers who live at Red Knoll, have ordered lemongrass and Thai green curry with some of the bonus credits from a successful year at their bank. Alex, from Irongates, the remote manager of a biorefinery, has ordered Henderson's Relish. There will be parcels from a variety of online retailers, delivered weekly through a pooled supply chain since the liquidation of Royal Mail in 2016 and the prohibitive cost of carbon credit for local distribution. He has three passengers today. Mrs Palmer is heading for the medical centre to follow up a tele-

consultation at the Hub. Although local equipment has been able to take a range of blood and tissue samples, the doctors want to perform a high-resolution scan on her suspected cancer and have authorized an issue of carbon credit to make the journey possible. The twins, Bethan and Trevor, whose parents run the GM willow plantation, will be very excited. They are leaving for a flight to Ethiopia using the one-off carbon allocation that is granted to 18 year olds who volunteer for a year's service to a developing country impoverished by the falling demand for their exports because of the carbon costs of transport. Mr Patel thinks of his extended family in Bangla Desh, who he last saw three years ago. He will not be eligible for a credit allocation for another two years, although there is talk that intercontinental air travel may soon be restricted to one return flight every ten years. Bethan and Trevor will probably be glad to get away for a while. Things have been rather poisonous in the village since the biomass stocks ran low at the end of yet another severe winter and the generator had to be switched off for parts of the day in February to conserve stocks. There was a lot of ill-feeling, especially when the Carbon Allocation Agency inspectors were called in by an anonymous person to fine some villagers who had opened up their old chimneys and burned unauthorized biomass to keep warm. However, it had given impetus to

the discussions about adding a community freezer to the Hub facilities so that the villagers could have lockers in the facility for storing produce rather than individual freezers. The extra credits could contribute to financing a biodiesel storage unit as a back-up to the wood-fired generator and the water wheel that had been rebuilt on the old mill race. The biodiesel unit would have to be big enough to cover the transport credits required to bring a biofuelled road tanker from the algae plant on the edge of the National Forest in Staffordshire.

It all seemed a long way from the days when Anwar's grandfather had bought the village shop and post office on the edge of Sherwood Forest. Back then, the Patels had been treated with great suspicion but now they were valued as key members of the community. They had survived difficult times – the economic collapse of 2018, combined with a succession of extreme weather events had shifted population and political values towards policies that emphasised strong regulatory interventions to create employment in environmentally-friendly industries and to develop a system of personal and community carbon credits. The latter would address the looming energy gap by reducing demand rather than increasing supply or shifting to renewable sources to sustain the same level. This strategy had freed capital for investment in other sectors and increased national

self-sufficiency in both energy and foodstuffs because farmers could only change land use with the right permits, which were regulated to prioritise domestic food production wherever land was suitable. The investments in biorefineries and local biomass generation only sustained about half the previous level of energy output. People had got used to not travelling, working remotely from each other and living in heavily insulated homes that needed little heating most of the time. However, many complained about the monotony of their diet, the lack of human contact with any group beyond a very small circle in their locality and the rather puritan policing of everyday life that went with this existence. Why hadn't they voted for change? Citizens who did not have a positive personal carbon credit balance were excluded from voting because their carbon overdraft indicated that they were not seriously accepting the responsibilities of citizenship, so that the franchise was now largely confined to enthusiasts for the vision of a low-carbon UK. Mass action was hard to organize where mobility was so limited and people's main connections were through ultra-high-speed broadband, which facilitated grumbling blogs but completely failed to threaten the government's hold on the country and its ability to push through its policies. Apparently the next challenge would be to reduce the UK population by licencing births...

## Using the Scenario

The choice of actions here will reflect your assessment of the groups involved. Some may prefer to concentrate on the assumptions and to think about how varying these might affect the picture of everyday life, while others prefer to focus on thinking about the story and what would have to be different for this to change. In some ways this is a more challenging scenario because it presents a much more radical change in social values than the previous ones.

- **Vary the technology.** Suppose there had been greater public resistance to GM willow, for example, so that local supplies of biomass were more limited? How might this impinge on public willingness to accept personal carbon credits and the regulatory environment that goes with them? Is it plausible to think that you could have high speed broadband alongside a relatively low-tech community? Some enthusiasts for a digital society think this is possible but you might want to reflect on how the equipment would be manufactured and installed under such a tight carbon

rationing regime. If that could not work, what would it do for the demand for mobility and the liquid biofuels needed to support that? Are there alternative biotechnologies that might enable the decentralization of liquid biofuel production so that this could be locally sourced rather than having to store solid biomass for burning in a generating plant? Would this be more efficient? Does it suggest an alternative research strategy to favour local biorefineries rather than large-scale plants serving a wide area and incurring substantial transport costs?

- **Vary the context.** This scenario has been deliberately constructed to depict a strongly Green context. Suppose that neither the economic crisis of 2018 nor a run of freezing winters and heatwave summers had been sufficient to disturb English voters into supporting a more communitarian approach and the country had stayed with a preference for market approaches, signalling costs and benefits through the prices of goods and services. How different would this village look? What would this mean

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for the supply and demand of biofuels? Where would they come from and how would they be processed? How would this affect international trade and the economic situation of poorer countries that might be exporters of either food or biomass? The scenario envisages a fairly static population. What issues might be raised by higher or lower birthrates? Would these affect the supply and demand picture for biofuels

• **Vary the narrative.** How would other people in this scenario describe their lives? Could a group develop narratives of what life would look like for each of them under the scenario assumptions? A school group might be particularly interested to explore the lives of Bethan and Trevor and what it would have been like for them to spend most of their lives within the sort of environment described. The village sounds quite affluent – where are the poor in this narrative? Personal carbon quotas have been proposed as a progressive measure because rich people use more carbon than poor people and may wish to buy surplus credits. Has this redistributed wealth or do the poor live somewhere else – in decaying cities, perhaps? Alternatively, perhaps city dwellers have a more familiar lifestyle because the urban areas can generate enough wealth to take up any carbon surplus created by self-sufficiency in rural areas and cover the transport costs. Perhaps the Carbon Allocation Agency is a regulator designed to discourage cheating or credit trading so that all emissions improvements are retained as a social rather than a private benefit. A group might be interested to discuss a day in the life of an agency inspector. Could that agency distribute energy access as well as carbon access? What would this mean for bioenergy, if this is not a particularly low-carbon source, even if it can be managed sustainably? (The carbon issues may come either from burning biomass or from the construction of biorefineries on a large scale.) Mrs Palmer, who is presented as being a potential cancer patient, might be an older woman in this narrative. What changes has she seen in her lifetime? How is she now supported? How would she be cared for if the diagnosis was definitely cancer? What does this mean for energy demand in general and the place of bioenergy within that mix? You might split a group into smaller units to work on different aspects and then bring them together to produce a shared story.

As before, there are various ways in which you could encourage a group to express their thinking and responses. Some groups might write their own stories but you could also use pictures or short video presentations. What does this village look like? If you are using it in a rural context with, say, a Women's Institute group, you could ask them to

survey their own community and think about its possibilities in terms of providing biomass relative to other renewables like water or wind turbines. They could look at the lives of representative individuals in the contemporary village and ask whether these could still be sustained in 2030. What part might biofuels play in, say, allowing affluent retired people to maintain a lifestyle that does not look very different from today because they can use their wealth to purchase greater access to biofuels. Are there ways to discourage or prevent this sort of the kind of inspectorate presented here? Suppose you have a retired director from an internet betting company living in the old manor house on the edge of the village? How does 2030 look to him and his wife – and their servants? What changes has it brought about to their lives compared with today? Perhaps he has bought hectares of land on which to grow biomass for private consumption – is it feasible to nationalize or collectivize this?

Once a group has explored the issues, you can ask them for an evaluation. Overall, do they think this is a gloomy picture or is it a future they could live with? How did it come about? What would policy makers and other citizens have to do to create a future that was more attractive to the group members? How would biofuels play a part within that?

### Scenario 4 Riding along on the crest of a wave...?

This represents the bottom-right box on the matrix, where biofuel technologies make rapid modest progress in a favourable environment. This scenario particularly stresses successful market strategies that bring biofuels into extensive use to explore what these might mean for everyday living – and whether they may be other strategies that could bring about the same result. As such, it tends towards a radical laissez-faire approach that has relatively few contemporary advocates but which allows a facilitator to ask exactly how far participants would be willing to go in adopting the values and lifestyle presented here. Remember that these scenarios are not predictions but tools to generate debate.

#### Scenario components

**Technology: Using synthetic biology techniques, algae are engineered to concentrate atmospheric carbon dioxide so that production can be located anywhere with a suitable supply of nitrogen-rich liquid waste. With other improvements in microbial technology for extracting oils and converting residues into animal feed, the result is a ready supply of oil for processing**

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### through conventional refinery technology into the current range of liquid fuel uses.

One of the major constraints on algal biofuel production is the need for a concentrated source of CO<sub>2</sub> as an input. Although it has been suggested that algal biofuel plants could be located adjacent to major CO<sub>2</sub> emitters like coal-fired power plants or certain types of chemical plant, this limits the range of locations and, hence, the achievable volume of production. It also assumes the continued operation of these plants, despite the pressures on these industries to develop low-carbon emission technologies. Atmospheric CO<sub>2</sub> alone is not sufficient to support growth levels that would be efficient enough to produce oil at a marketable cost. If it could be concentrated within the algae production system, then plants could be established anywhere with a sufficient supply of nitrogen-rich liquid waste, whether from human sewage, animal production or agricultural run-off. In theory, the result could be a virtuous system that would both remove atmospheric CO<sub>2</sub> and clean waste water before its return to the environment. The residues would potentially substitute for cattle cake and molasses in animal feed: the resulting diet also seems to reduce methane emissions from cattle, which is a further environmental benefit.

#### Context

### Competing Energy Technologies: Biofuels dominate the market

Traditional oil companies have made major investments in the development of algae-based processes, as sources of liquid biofuels that are more or less identical to those with which they are familiar. The rapid and early success of this investment means that alternative, electric-based technologies are stillborn. Neither consumers nor engine manufacturers nor governments are willing to make the additional changes necessary to move to electric-based modes of transport. Liquid biofuels flow through existing supply chains to existing uses in power generation and transport. Battery, fuel-cell and hydrogen technologies are all displaced, although electricity continues to spread as the main power source for fast rail transport, because of other advantages. However, it is generated by the combustion of biodiesel, which displaces first oil, then coal and finally natural gas as power sources. Because the price tends to be at the upper end of the range for oil, there remain incentives to improve efficiency in use, through building insulation, rooftop solar panels and improvements in engine and generation technology, but there is little demand for other forms of generation and most wind farms are rapidly dismantled for scrap.

## Climate and Environment

### Climate: Neutral

Although climate change continues to be a matter of social and political concern, the containment of demand by responses to changing prices and the substitution of biofuels for coal and gas-fired generation has lessened the perceived urgency of the challenge for the UK. The country is projecting a slow decline in carbon emissions, although remaining above the levels that some climate scientists regard as optimal because biofuels are low-carbon rather than zero carbon. However, the enthusiastic response of the US and China to liquid biofuels has taken some of the pressure off other countries, although the vested interests of the US coal mining industry have restrained the full potential of biofuels to displace hydrocarbons. Global warming is following a low to median track in the IPCC estimates and is seen as a problem manageable by further technological development rather than major social or economic changes. This might, for example, involve atmospheric bioengineering by continuing to develop algae strains for their carbon-fixing rather than their oil-generating qualities

### Environment: Neutral to Adverse

Climate change has had some impact on marginal subsistence agriculture, particularly in Africa and parts of Central Asia, producing localized problems of population movement. It has also made some traditional Southern European holiday destinations uncomfortably hot during the summer months. However, the most important change has been the collapse in demand for biomass crops and for hydrocarbons, which has had a devastating impact on incomes in many developing countries. Although these are suitable sites for algal production, the closed systems that have developed are highly automated and require very little labour input. Famine and food riots have developed in some areas because people lack the income to buy food rather than because of absolute shortages. Ecosystem management has become highly problematic because unused agricultural land does not necessarily become an environmental asset unless it is returned to nature in a planned way rather than just being abandoned.

### Socio-Economic

### Economic: High-growth

The UK economy has bounced back from the 2008 economic crisis, taking advantage of the spare capacity in its manufacturing sector and the flexibility of its labour market to grow rapidly. As an early adopter of the new algal biofuel technology, with few sunk costs because of

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its dependency on imported energy, it has sustained this growth pathway where less flexible European competitors have lagged. UK living standards have rapidly recovered the ground lost after 2008 and the availability of low-cost energy and transport networks has brought peripheral regions securely into the national economy. Policy concerns are mainly about inflation and over-heating brought about by full employment.

### Demographic: High-growth

The buoyant UK economy has sucked in labour from all over Europe and beyond, mainly among the 20-35 year old age groups. The economic problems in developing countries have led to additional illegal migration among the same groups, although the rapid rate of job creation has meant little concern about the implications of this: the economy can absorb everybody who wants to work and still end up with localized shortages. The ratio of the working age to the retired population has improved, although this migration has aggravated the problems elsewhere in Europe. Many of these migrants are establishing families in the UK and showing signs of becoming permanent residents.

### Location: Neutral

London continues to have a stronger demand for labour than most of the rest of the UK but cheap energy and low transport costs have dispersed growth to a greater extent so that there are only small pockets of social exclusion, mainly in areas where there is a long-established culture of disengagement from employment and a lack of education and skills to participate in the labour market. In principle, though, young people can get good jobs in any region. There is considerable pressure on the housing market from people wanting to establish their own households with implications for urban sprawl and long-distance commuting.

### Culture and Values: Generally pro-market

At least since the 13th century, the English have tended to have a more individualist approach to life than their European neighbours, with occasional brief interruptions. The political culture continues to emphasise market-oriented values and to design social institutions around these. The successful reconstruction of the economy since 2008 is held by many to be a vindication of this tradition.

### Everyday Life in 2030: The Rewards of Initiative

Guy Morley shuffled the cushions on his sun lounger and adjusted the gold chain on his bronzed torso. His wife, Joy, sprayed one of the new nanotech tanning compounds over her shoulders and thighs. Although there had been some early cancer scares, recent formulations had proved entirely safe and had superseded traditional sunscreens. By penetrating into the surface of the skin, these compounds gave more effective protection against burning and skin ageing, and lasted longer per application. Guy looked up at the cruise ship's funnel which dispersed a virtually invisible stream of smoke into the hot African air. He was old enough to remember when ships burned the crudest of bunker oil – the world's shipping collectively emitted more CO<sub>2</sub> and other pollutants than many small countries. Now they had all converted to bio-bunker grade at a fraction of the cost and the smoke-blackened stacks of the past were the stuff of poems and historical novels.

Guy reflected on the part he had played in this process. He had studied bioscience at a relatively unfashionable university and gone on to work as an investment consultant, appraising small biotech companies on behalf

of a group of venture capitalists. However, he had not lost his own interests and spent a lot of evenings playing around with synthetic biology kits that he ordered on the internet. 'Garage biology' it was called in those days, although he actually had a garden shed rather than a garage. A lot of people were throwing money into algal biofuels around 2010 but most of this was going through big corporations and public bodies into big research universities so that everything was regulated and gold-plated. Guy and his friends just chucked things together to see what happened. In the end, garage biology got a bad name after some jokers created an otherwise harmless virus that accelerated melanin production and slipped this into the drinks of a couple of interns working at the US Congress. A week of bright orange-skinned legislators did not do much for the dignity of the House, although it led to major investments in anti-viral research and strict regulation of access to synthetic biology components. Guy got lucky, though. He assembled an algae that could concentrate atmospheric CO<sub>2</sub> to accelerate its own growth and saw the potential. A college friend who had trained as a patent agent took care of the legalities and he used his own connections to line up some sharp-eyed venture capitalists. His first wife, Kate, had objected to securing a bank loan on the house, but he hadn't

noticed her complaining with the way the royalties now sustained her lifestyle. He had run the company for ten years or so while his team improved the strain, developed closed production systems, to minimize the risk of contaminating either the environment or the algal strain, and consolidated the patents before selling out to a major oil company and settling down to enjoy the abundant wealth and leisure that a combination of skill and luck had delivered.

His teenage daughter, Bethan, weaved through the bodies around the liner's pool and pushed up the sleeves on her cheesecloth shirt to show him the bruises that she had got when she and her twin brother, Trevor, had gone ashore with the excursion yesterday. West Africa was having a pretty bad time at the moment. The collapse in the hydrocarbon oil market had led to a major crisis in urban employment – they had sailed past the rusting hulks of abandoned oil rigs for most of the previous day. The farmers who had switched to growing biomass crops for fuel had seen their market disappear and the rapid growth of unemployment meant that they could not move back into food crops because there was no market for these either. The ports were now full of desperate beggars and the shore excursions were accompanied by security guards who chaperoned the passengers around historic sites and carefully screened shopping malls. However, it did not take much to lose track of the tour – Bethan had lingered to look at some jewellery and it was fortunate that Trevor had stayed with her. The guards had come quickly enough once the fracas had started and Bethan began screaming but Trevor was also nursing a few bruises and some cuts on his knuckles where he had discouraged a few beggars. A good reason to avoid the excursions, thought Guy, but it was not a bad

idea that young people should see for themselves what decades of corruption and dependency on handouts from international aid and well-meaning charities led to.

Back home, life was better ordered. Cheap, low-carbon fuels had led to rapid economic growth, which had been facilitated by low personal and company taxation. There had been some problems, of course. The demand for larger and more spectacular houses, given the real decline in heating bills, had built up pressures for urban sprawl and long-distance commuting, although these were tempered by the extension of mobile working from homes and local office hubs. Many cities had brought in congestion charges, which priced less affluent workers out of car use at peak times and onto the ancient buses run by small independent operators along the major arteries, like the *colectivos* of South America. Guy's cleaner, Mrs Palmer, is always complaining about how much time she spends waiting on street corners for buses that are always dirty and overcrowded. Fuel efficiency was no longer a particular concern so cars were being restyled with revival of the 1950s chromed fins and bumpers in a constant contest with attempts to constrain design in the interests of safety. Supermarkets were constantly replenished with exotic foods and flowers brought in by air from all corners of the planet. Of course, there were malcontents as well, who complained about the social divisions accentuated by this abundance, but looking at the Africans fighting for scraps, Guy concluded that even poor people in England had a standard of living way in excess of their basic needs – providing they were willing to work for it. Some climate scientists were beginning to warn about the consequences of consuming so much CO<sub>2</sub> but they were obviously the sort of people who could never see anything positive in economic growth and personal affluence...

## Using the Scenario

The choice of actions here will reflect your assessment of the groups involved. Some may prefer to concentrate on the assumptions and to think about how varying these might affect the picture of everyday life, while others prefer to focus on thinking about the story and what would have to be different for this to change. This scenario has been particularly designed to help people think about the challenges that could be presented by abundance, and to discuss their global consequences.

- **Vary the technology.** This technology might play out in two rather different ways. One would be in open systems, where the algae would be cultivated on ponds deriving energy directly from sunlight but with risks of the escape by the modified organisms or contamination by wild species. The other might be in closed systems where the algae are fully confined and energy is introduced by lighting systems. The risks of escape and contamination would be lessened but the capital investment might be greater and the energy yield might be less (although the containment might allow more aggressive organisms to be used in the productive

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process. Contrasting these versions would enable a group to think about safety and regulation issues, and about the relative portability of technologies that depend on more or less capital investment. Would the African situation be so dire, if the system simply used open ponds and sunlight, which Africa has in abundance compared with Northern Europe. Facilitators might think this scenario is less plausible biologically than some of the others, in which case they could create their own game-changing innovation. The important thing is to have a scenario within the set that yields abundant cheap energy in order to introduce balance into the discussions.

- **Vary the context.** This scenario assumes that demands for other fuels would collapse if more or less unlimited cheap supplies were available from algal sources. The liquid fuel would immediately occupy the present niches in the energy system that are taken by liquid hydrocarbons as well as displacing natural gas and coal. It refers to the scrapping of wind turbines: presumably, this would apply to most other renewable technologies. Could these compete? What would they have to do? The scenario also draws attention to possible economic consequences for African countries of a sudden lack of demand for oil or for biocrops. Which other countries might be affected? Would they be affected in the same way? How would this loss of income be made up? Would it be practical to build algal plants on the edge of African cities to process large volumes of human waste - although these plants are unlikely to create much employment if they are contained systems? If groups suggest that farmers could avoid famine by switching to food crops, facilitators might point out that famines do not occur because there is an absolute shortage of food but because the people who are starving are unable to pay enough to encourage the movement of food to the point of need. In fact, switching from biomass to food production could make the situation worse by growing more food than the market can absorb, driving down prices and making more people unable to generate enough income to buy the food they need.

- **Vary the narrative.** How would other people in this scenario describe their lives? Could a group develop narratives of what life would look like for each of them under the scenario assumptions? Look at some of the other characters in the story. Maybe Kate, Guy's first wife, left him because she disliked the changes that wealth brought.

What do you think the life of a wealthy but socially more responsible person would like in this age of abundance? Mrs Palmer, Guy's cleaner, is a poor person in this rich age. What would her life be like with the real price of energy back to, say, the levels of the 1960s? The twins have grown up in a privileged environment. How do they see energy in their lives? Could you explore the perspectives of some of the African characters thinking about how their lives have changed within a short period? Do not forget the jewellery trader who may make a good living from the tourists and have little time for the street beggars around her. What does this mean for energy demand in general and the place of bioenergy within that mix? You might split a group into smaller units to work on different aspects and then bring them together to produce a shared story.

The twins' encounter with Africa might be a good topic for a short play, with some of the African characters describing the changes in their lives and how they came to hustle these white teenagers so aggressively. The twins could describe their lives in England and what it is like to live in a rich country with cheap energy. The play might come out of the exchange in the market so you could also look from the point of view of the jewellery trader who may make a good living from the tourists and have little time for the street beggars around her. Suppose the incident had been more serious. Could you write stories about the way it might be covered on different newspaper websites and the conclusions they might draw about the consequences of cheap energy? Would a documentary film maker celebrate the affluence of the English or emphasise the degree to which cheap energy had aggravated social divisions?

Once a group has explored the issues, you can ask them for an evaluation. Overall, do they think this is a future they could live with? How did it come about? What would policy makers and other citizens have to do to create a future that was more attractive to the group members? How would biofuels play a part within that? Working with Scenarios

## Working with Scenarios

Scenario 4 was used as the basis of a pilot exercise at the Cheltenham Science Festival in 2011.<sup>1</sup> The participants were a group of about thirty five people, predominantly middle-aged to elderly with a wide range of previous knowledge. There was a slight excess of male participants and no-one

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<sup>1</sup> This involved Robert Dingwall, Andy Balmer and Murray Goulden from the drafting team with Patrick Middleton (BBSRC), Marcelle McManus (University of Bath) and Jonathan Scurlock (NFU). Particular thanks are due to Andy Balmer who led the session and prepared useful supplementary materials.

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visibly from a minority ethnic background. A significant minority seemed to have brought some expertise of their own from engineering or agriculture. The format challenged the expectations of some participants and an estimated 20-30 per cent left when they discovered that it was not a conventional lecture with questions but involved interactive group work. We ended up with two groups of about 10-12. Those who remained generally found the session an interesting experience and were sympathetic to the teething problems that emerged. A particular attraction was the recognition that they were not being told what to think but to use information and their own experience within the group. They were particularly interested to learn about second and third generation biofuels and the way in which research was moving towards sources that did not compete directly with food crops.

On the basis of this experience, it is recommended that facilitators should begin by introducing the matrix, underlining the interaction between science and society, and then making two short presentations, one summarizing the technology issues and one the context issues. This part of the event should take no longer than 20 minutes. Younger audiences who are more familiar with group work could probably deal with a scenario in one hour but less experienced groups may need rather longer, possibly another half hour, or more input from the facilitator. On this occasion, Dr Balmer had prepared some stimulus cards which helped to focus the discussion and Professor Dingwall had prepared a slideshow of images linked to the chosen scenario, although this was not used. (Copies of these are included as an appendix to this document). 30 minutes could then be allocated for feedback and general discussion, keeping within a 2 to 2 ½ hour time slot. There is certainly merit in having multiple groups to generate a wider range of views and ideas but it may be difficult to deal with more than three in a session of this kind.

Of course, there are other possible uses of the scenario materials that could be adopted if there were more time available. Some of the suggestions about groups developing video materials suitable for an outlet like YouTube, for example, could be a focus for work over a number of sessions or a whole day event. While school or student participants might seem an obvious focus for such types of engagement, other community groups should not necessarily be excluded from consideration. Video-making could be an interesting engagement tool for groups like a Women's Institute or a meeting of retired people. Nevertheless, the Cheltenham pilot established the basic

viability of the scenario tool in a relatively traditional public engagement format, allowing for the evident resistance of some people to the departure from a conventional didactic lecture and questions model.

## The Scenario approach

These scenarios are intended to be used as part of a wider toolkit to promote public engagement with science and policy in relation to biofuels. As we have outlined our approach, we have tried to develop a strategy that makes the foundations of scenarios more transparent and to illustrate ways in which they can be converted into everyday narratives that public engagement facilitators can use to stimulate group activities. We have particularly tried to construct these narratives so that they can either be a resource that facilitators can easily adapt to the particular audience that they are working with or simply take off the shelf. In the final two chapters, we will present the evidence from which our scenarios are devised in a more formal fashion. This will allow facilitators who are concerned about the plausibility of the scenarios or narratives to dig deeper into the evidence base and, if they wish, to use that evidence to make their own adjustments to the scenarios. However, where possible, we have also tried to identify authoritative websites that can be used to update the scenario assumptions in the light of technological or contextual developments, thereby extending the life of the document.

## Chapter 3 Technologies

An extensive review of the scientific literature suggests that there are currently 8 biofuels that have some serious prospect of reaching the market before 2030. Some are already in use, while others are more at the stage of showing promise in laboratory work. Their development was summarized in Chapter 1, using the table below, which also indicates the structure of this chapter, where we discuss the scientific position in more detail as a basis for scenario design. We shall conclude by noting some web sites that facilitators could consult to update what has been said here and ensure that scenarios reflect the most recent available evidence.

### Biomass Sources

Before discussing each of the fuels listed above, a few general comments on biomass may be helpful. 'Biofuel' is a term used to describe many different kinds of product that all, in one way or another, derive from 'biomass'. Biomass refers to living or recently harvested biological material, such as plants, plant residues, wood, and biological waste from industry, agriculture or municipalities. Successful biofuels will have to be produced with much lower life-cycle greenhouse-gas emissions than traditional fossil fuels and little or no competition with food production. This is a particular problem for so-called 'first generation' biofuel production that relies on the use of biomass which comes directly from food crops, such as corn (see ethanol, below). Although wild or marginal land could be cleared or brought into production, this may still compete with its use to achieve food security, and raise issues about wildlife conservation

and the protection of biodiversity. In recognition of these concerns, BBSRC does not fund any research on 'first generation' technologies.

The main focus of work at present is in the uses of wastes or non-food crops. Wood from forestry operations represents an abundant resource (Solomon and Luzadis, 2009) as does municipal and industrial waste (Tilman, Socolow et al., 2009). One benefit of using wood from forest sources is that, if managed sustainably, they can lower CO<sub>2</sub> emissions (Volk, Verwijst et al., 2004). Over-reliance on forest sources could, though, have significant implications for the protection of natural ecosystems and of biodiversity (Solomon and Luzadis, 2009). Food crop residue is another potential source of biomass: e.g. the corn stover or straw from rice. However, research has indicated that it is to the benefit of farmers to leave substantial quantities of crop residues on the land (Wilhelm, Johnson et al., 2007), which may turn out to be a significant problem for this strategy. Biomass crops could be grown on land that has been abandoned for agricultural use, which would avoid direct competition with food crops, minimize the potential for direct and indirect land-clearing and contribute to biodiversity. It is argued that, if managed properly, use of degraded lands for biofuels could increase wildlife habitat, improve water quality, and increase carbon sequestration in soils (Tilman, Socolow et al., 2009). Biofuel biomass might also be grown in between the seasons of planting and growth of the food crops (Heggenstaller, Anex et al., 2008).

BBSRC research is investigating ways in which to improve the amount of biomass that can be harvested from

Biofuel	Process	Status	Engine application
Bioethanol	Microbial	Industrial	Pure/blend
ETBE	Chemical/microbial	Industrial	Blend
Biomethanol	Thermochemical/microbial	Pilot plant	[Pure/blend] MTBE/biodiesel
Biobutanol	Microbial	Pilot plant/industrial (until ca 1990)	Pure/blend
Biomethane	Microbial	Industrial	Pure/blend
Biohydrogen	Microbial	Laboratory	Bioethanol (Syngas)/pure
Biodiesel	Physical/chemical (enzymatic)	Industrial (laboratory)	Pure/blend

Miscanthus and Salix species, without requiring additional investment in fertiliser and other inputs. <http://www.bsbec.bbsrc.ac.uk/programmes/perennial-bioenergy-crops.html>

There is also potential for algae, yeasts and bacteria to be biomass sources. These are discussed in the section below on biodiesel.

## Bioethanol/ETBE

Ethanol is not an ideal fuel molecule, mostly because it is incompatible with the existing fuel infrastructure for distribution and storage owing to its corrosivity and high hygroscopicity (the ability to attract water molecules); moreover, it only has about 70% of the energy content of petrol (Stephanopoulos, 2007; Lee, Chou et al., 2008). Ethanol may, in the future, represent an important chemical feedstock for plastics production. One potential use in this direction would be for conversion into ethylene, the monomer of the extremely important plastic, polyethylene (PE). Research on catalysts for this reaction has been developing in recent years (Ouyang, Kong et al., 2009).

Despite its limitations, much work has been conducted on ethanol. It is already regularly blended with gasoline. In the United States, nearly all ethanol is blended into gasoline at up to 10 percent by volume to produce a fuel called E10, though higher blend alternatives E85 or E100, those being 85% and 100% respectively, are available. In 2005, total U.S. ethanol production was 3.9 billion gallons<sup>2</sup>, which had risen to over 9bn gallons in 2008 (see graph below: 'U.S. Production, Consumption and Trade of Fuel Ethanol'). Ninety five percent of all ethanol produced in the U.S. derives from corn feedstock using fermentation techniques by *Saccharomyces cerevisiae*<sup>3</sup> (a species of budding yeast). Conventional engines can support the E10 blend (10% ethanol, 90% gasoline) but E85 requires modified engines due to its corrosive nature. The conversion of ethanol into ethyl tert-butyl ether (ETBE) may be more promising, since it is less affected by the presence of water and could represent a better way of blending ethanol into existing fuels, but this would still require initial production of ethanol.

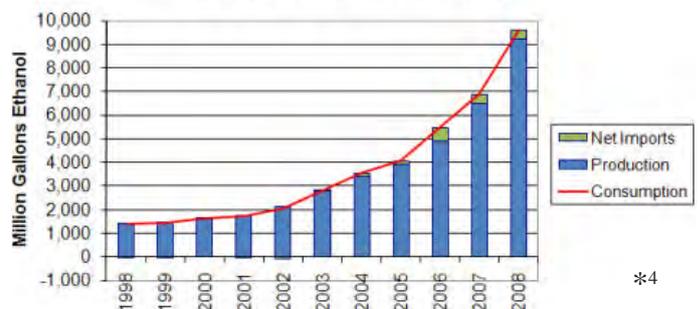
Since 1975, with the initiation of the National Alcohol Fuel Program (ProAlcool) in Brazil, demand for bio-based production of ethanol in that country has fluctuated in response to political and economic priorities (Rosillo-Calle

and Cortez, 1998). As the sugar-ethanol industry matured, policies evolved and the ProAlcool program was phased out in 1999, permitting more incentives for private investment and reducing government intervention in allocations and pricing (Balat and Balat, 2009). Widespread availability of flex-fuel vehicles (promoted through tax incentives) combined with rising oil prices have led to rapid growth in bioethanol and sugar cane production since 2000. In 2009, more than 80% of Brazil's automobile production has flexible-fuel capability, up from 30% in 2004. With bio-ethanol widely available at almost all of Brazil's 32,000 gas stations, Brazilian consumers currently choose primarily between anhydrous bio-ethanol/gasoline and a 25% bio-ethanol/gasoline blend on the basis of relative prices (Balat and Balat, 2009).

Contemporary spark ignition engines have to be modified for mixtures above 7% (or 10% depending on climate) ethanol to gasoline (thus modification is essential for E85 and E100). The modification technology is installed in so-called flex fuel vehicles (FFV). Most car companies now offer FFVs, e.g. as "Totalflex" (VW) or "Flexpower" (Chevrolet/Opel/GM). In Brazil, 3 million FFVs have been sold to date, and in Sweden, 15,000 FFVs were sold in 2005 alone. Bioethanol can be run in diesel engines, but additives are necessary to prevent phase separation (Lapuerta, Armas et al.).

Many argue that ethanol burns relatively cleanly, especially as the amount of gasoline with which it is blended decreases. Evaporative and toxicity-weighted air toxics emissions are consistently lower for ethanol than for gasoline (Lynd, 1996). The picture is more complicated, though, if one takes account of ethanol, ethanal and nitrogen oxide emissions (Niven, 2005).

**U.S. Production, Consumption, and Trade\* of Fuel Ethanol**



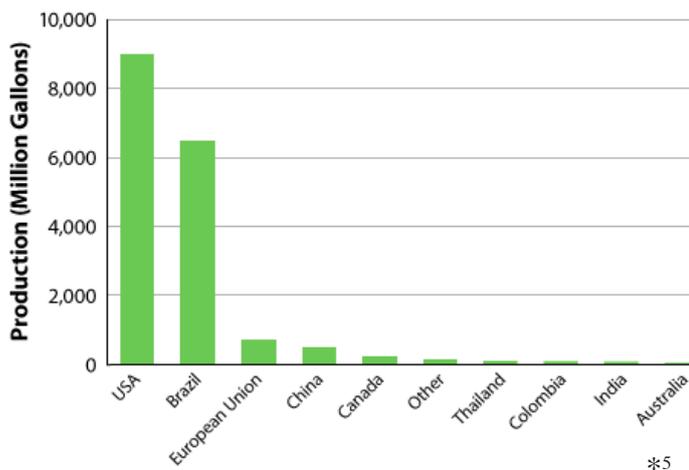
\*4

<sup>2</sup> or 2.9 percent of the total gasoline pool

<sup>3</sup> [https://www.biofuelsdatabase.org/wiki/index.php5/Ethanol\\_Pathway](https://www.biofuelsdatabase.org/wiki/index.php5/Ethanol_Pathway)

<sup>4</sup> \*Trade includes small changes in stock. Source: Energy Information Agency (EIA) [http://www.afdc.energy.gov/afdc/data/docs/ethanol\\_production\\_consumption.xls](http://www.afdc.energy.gov/afdc/data/docs/ethanol_production_consumption.xls)

**World Fuel Ethanol Production, 2008**



As a first generation biofuel, ethanol is produced by the conversion of cellulosic biomass. The feedstock crops so far recommended for conversion to cellulosic ethanol have a high amount of cellulosic biomass: corn, rice and sugarcane. Other sources include fast-growing perennial grasses such as switchgrass and giant miscanthus, and woody crops such as poplar and shrub willow (Sticklen, MB, 2008).

Depending on where they are planted, the ideal characteristics of non-food cellulosic crops include: use of the C<sub>4</sub> photosynthetic pathway (the more recently evolved and efficient carbon fixation pathway); long canopy duration; perennial growth; rapid growth in spring (to out-compete weeds); and high water-usage efficiency (Sticklen, MB, 2008).

The earliest and simplest of methods for producing fuel from biomass is the conversion of starch or sugars. The cost of producing ethanol in this manner is linked, in part, to the inescapable loss of half of the carbon during fermentation of sugars by microorganisms. Although the production of ethanol from cane sugar is a relatively simple process (as is done in Brazil), complexity increases when ethanol is produced from corn or wheat starch (as is done in the USA), as these processes require enzymes to hydrolyze starch to glucose prior to fermentation (Mielenz, 2001).

Although corn could yield up to 13 billion gallons per year, US production of ethanol already utilizes 23% of the corn crop and is causing economic problems such as elevated costs of corn for human consumption and for animal feed.

Furthermore, ethanol from corn has only supported 2% of the national transportation requirements. If the projected ethanol demand were to be fulfilled exclusively with corn, it would require more corn than the US currently produces, and would dangerously compete with food crops. The limited availability of corn and a restricted capacity to expand its production due to infrastructure constraints puts a ceiling on corn to ethanol production goals<sup>6</sup> (Farrell, Plevin et al., 2006). However, the US Department of Energy predicts that steady improvements in corn yield will continue, providing an increase of 2.33 bushels per acre by 2015, which would equate to increased availability of corn (1.17 billion bushels), expanding corn yield to 15 billion gallons of ethanol by 2015<sup>7</sup>. This would be the highest amount of ethanol that corn crops could contribute to biofuel production in the USA since use of corn is capped at 15bn, with alternatives being required to satisfy the further 1bn gallons that are mandated to come from cellulosic biofuels by 2022<sup>8</sup>.

Second and third generation production of ethanol relies on the conversion of lignocellulosic biomass (the bulk of the crops – e.g. the stems), which significantly increases the complexity of fuel production processes because of its structural complexity. Lignocellulose is difficult to hydrolyze because it is: (1) associated with hemicelluloses (a complex sugar molecule containing many monomer sugar molecules, including xylose, mannose, galactose, rhamnose and arabinose); (2) surrounded by a lignin seal (lignin is the hardening molecule found in structural parts of plants and trees, which has a limited covalent (an extremely strong type of bond) association with hemicellulose; and (3) much of it has a crystalline structure with a potential formation of six hydrogen bonds (the strongest of the intermolecular forces), four intramolecular and two intermolecular, giving it a highly ordered, tightly packed structure (Weil, Westgate et al., 1994). This complex and hardened structure means that various pre-treatment methods are currently used to disrupt the lignocellulosic matter and to remove most of the lignin, thus allowing the cellulases to access the cellulose and thus convert it into usable molecules for fuel. This inability to directly degrade the lignocellulosic matter is a major technological and economic limitation in the development of biofuels. Much current research is attempting to avoid

<sup>5</sup> Source: Renewable Fuels Association, 2009 [http://www.afdc.energy.gov/afdc/data/docs/world\\_ethanol\\_production.xls](http://www.afdc.energy.gov/afdc/data/docs/world_ethanol_production.xls)

<sup>6</sup> <http://www.bio.org/ind/GrowingEnergy.pdf>

<sup>7</sup> [http://www1.eere.energy.gov/biomass/pdfs/effect\\_of\\_corn\\_yield\\_improvements.pdf](http://www1.eere.energy.gov/biomass/pdfs/effect_of_corn_yield_improvements.pdf)

<sup>8</sup> [http://www1.eere.energy.gov/biomass/ethanol\\_myths\\_facts.html](http://www1.eere.energy.gov/biomass/ethanol_myths_facts.html)

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this limiting step (either by using microbes that can directly degrade lignocellulosic biomass – see below, or by improved enzyme chemistry). There are also physical pre-treatments, such as torrefaction (heating the biomass in a closed environment) prior to grinding the resulting materials for use as substrate so that the lignocellulosic matter is disrupted prior to microbial action (Chiaramonti et al. 2011).

Pretreatment chemistries vary from very acidic to quite alkaline. Each has different effects. Acid pretreatments hydrolyze the hemicellulose while leaving the cellulose and lignin intact in the residual solid. Alkaline approaches tend to have more of an effect on the lignin component and leave both hemicellulose and cellulose intact. Both of these methods require enzymes to digest both hemicellulose and cellulose, and the enzymes are quite expensive. Pretreatment with acids and alkalis can result in high concentrations of unwanted chemicals: furfurals when using acids; ferulate and acetate when using alkalis. These compounds will be present in the sugar stream. Because they can be quite toxic to microorganisms, they can have serious effects on the productivity of a bioreaction process (Gray, Zhao et al., 2006).

The aim in developing new methods of pretreatment is to be able more effectively to conduct the degradation of the lignocellulosic biomass at the same time as fermenting the ethanol (which is known as simultaneous saccharification and fermentation [SSF]). However, there is likely to be a gap between these two processes since the reactions do not work at the same rate (Hahn-Hägerdal, Karhumaa et al., 2007) and there does not currently seem to be an obvious method of getting past that difficulty. SSF typically lasts 3 to 6 days, with the product being a dilute ethanol stream of ~ 4.5 % from which ethanol is then separated by distillation (Stephanopoulos, 2007).

In order to make the system more efficient at degrading lignocellulose biomass and fermenting ethanol, research is being conducted in two broad directions: engineering of the biomass and engineering of the microbes.

## Engineering the biomass

The primary plants of interest for genetic engineering are those that use the C4 photosynthesis pathway. The C4 group of potential energy crops includes various perennial grasses such as switchgrass and *Miscanthus*. These grasses have the advantages of not requiring replanting after a yearly harvest, rapid growth, high biomass density per unit area, and low nutrient and water needs, enabling growth on

marginal agricultural land. Disadvantages are that C4 plants are rare in cold climates and unable to grow at temperatures below 10 degrees Celsius. In this environment trees, which exclusively depend on C3 photosynthesis, such as poplar, willow and eucalyptus, provide the only candidate species (Rubin, 2008).

A significant challenge in the drive for more efficient ethanol production processes is to develop crops with a suite of desirable physical and chemical traits while increasing biomass yields by a factor of 2 or more. Although many annual crops benefit from centuries of domestication efforts, perennial species that could play a central role in providing a renewable source of feedstock for conversion to fuels and materials have not yet had comparable attention (Ragauskas, AJ, Williams et al., 2006).

An obvious target is manipulation of photosynthesis to increase the initial capture of light energy, which at present is less than 2 % (Ragauskas, AJ, Williams et al., 2006). Plants also typically invest considerable energy in making reproductive structures. If flowering can be delayed or prevented, this energy may be transferred into increasing the plant's overall biomass (Ragauskas, AJ, Williams et al., 2006).

The primary means of increasing biomass through genetic engineering will be to alter the genetics of the plants and trees so as to maximise biomass yield per land unit area (Rubin, 2008). In order to do this much more work will have to be carried out, beginning with the sequencing of those crops that represent the best natural candidates for biofuels in particular climates and of those crops with particular features (e.g. short, wide stature) that could be mined for their genes for transformation into the best candidates. Work in this direction includes such things as the over-expression of gibberellin biosynthesis in trees, which resulted in significantly increased growth (Eriksson, Israelsson et al., 2000).

Other genes of primary interest will be those involved in the biosynthesis of cellulose and hemicellulose but our understanding of many of the steps in those pathways (despite decades of study of cellulose synthesis) is quite immature (Bolwell, 2000; Persson, Wei et al., 2005). Pathways of importance for future research will include those responsible for carbon allocation, uptake of CO<sub>2</sub>, use of nutrients, oxygen and water, respiration and control of the light-dark cycle (Sticklen, MB, 2008). Finally, understanding and modifying the lignin synthesis pathway could dramatically alter the requirements of pretreatment,

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but again our current knowledge has some important gaps (Ragauskas, Arthur J., Williams et al., 2006 ).

A further approach to reducing the costs of bioethanol synthesis is to engineer the plant to be digested with the genes that produce the enzymes used to degrade cellulose/hemicellulose in the bioreactor. That would mean that pretreatment would release the stored enzyme (stored in such a way as to not simply degrade the organism itself as it produced the enzyme) and thus obfuscate the enzyme-addition step and move the process closer to SSF (Sticklen, M, 2006). Genetic engineering may also modify the lignin wrapping of the cellulose and facilitate breakdown by hydrolysis (Z Li et al. 2011).

BBSRC has several programmes of research investigating the structure of biomass crop cell walls and lignin structure, better to understand the genes that control their composition, the enzymes that facilitate their degradation and the components of the wall that resist these enzymes. The research also seeks to understand enzymes used by macroorganisms to digest wood and to find ways to utilise these enzymes in industrial degradation processes.

<http://www.bsbec.bbsrc.ac.uk/programmes/cell-wall-sugars.html>

<http://www.bsbec.bbsrc.ac.uk/programmes/cell-wall-lignin.html>

<http://www.bsbec.bbsrc.ac.uk/programmes/marine-wood-borer-enzyme-discovery.html>

## Engineering the Microbes

Microbes are currently envisioned as offering the most promising engineering opportunities within the biofuel production process, though – as one would expect – the work is still in its infancy (Dellomonaco, Fava, and Gonzalez 2010). The major benefit from engineering microbes for biofuel production would be in the direct degradation of lignocellulose, i.e. avoiding pretreatment. This would be significantly useful since the production of lignocelluloses is not reliant on agricultural resources commonly used for food, such as corn, sugar cane, soybean, and palm oil. The development of cost-effective and energy-efficient processes to convert lignocellulose into fuels faces considerable challenges, most notably the severe lack of genetic engineering tools for the non-model organisms that are capable of directly acting on lignocelluloses (Lee, Chou et al., 2008), and the difficulties in optimizing metabolic pathways and balancing the redox (reduction and oxidation

of molecules in pathways) state in the engineered microbes (Mukhopadhyay, Redding et al., 2008).

The best strategy is seen to be the use of model organisms that are well established in industrial-scale fermentations, i.e. *E. coli* and *S. cerevisiae*. These model species have well-characterized genetics and the genetic tools for manipulating them are good starting points for development as production platforms (CR, D et al., 2008). Because these host organisms are also facultative anaerobes (they do not require oxygen for their processes and thus do not require expensive aeration facilities) with fast growth rates, largescale production processes are more feasible than the non-model species that naturally digest lignocellulose (Ingram, L.O., Aldrich et al., 1999).

An immediate problem with the generation of more ethanol (by whatever process one chooses) is going to be the intolerance of the microbiological components to the alcohol. One of the most important engineering projects of the coming decades will be to develop an ethanol-tolerant strain of a model-organism, that is (ideally) able to degrade the lignocellulose and ferment the sugars into ethanol (Stephanopoulos, 2007).

One of the products of the breakdown of hemicelluloses is xylose (produced by xylanase enzymes). In order to perform both steps (sugar release and fermentation) in the same organism, there are two approaches: either introduce the ethanol pathway in natural xylose consumers (Ingram, L O, Conway et al., 1987) or engineer the xylose-catabolizing pathway in natural ethanol producers (Kuyper, Harhangi et al., 2003).

An increasingly important bacterium in biofuel production is *Zymomonas mobilis* because its fermentation produces only ethanol (whereas other species produce side-products such as acetic acid, which is the case in *E.coli*, for example). The transfer of the genes required for this ‘homoethanol’ pathway have been engineered into *E.coli* with reasonable success (LO, T et al., 1987). Despite *Z. mobilis* being more efficient at ethanol generation, its major weakness is that it only digests glucose, fructose and sucrose sugars, which is no use if we want to stick with 2nd and 3rd generation fuels. Thus, attempts have been made to engineer the xylose-degrading enzyme genes into *mobilis* (Zhang, Eddy et al., 1995), or arabinose (Deanda, Zhang et al., 1996), either of which would enable it to degrade parts of hemicellulose in lignocellulosic biomass. One efficient strain developed for this purpose is strain ZM4 (Joachimsthal and Rogers, 2000). Work since the creation of this strain has

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focused on increasing the ethanol concentration and the microorganism's resistance to the products.

Some strains of *E.coli* and *Z. mobilis* are being considered for commercial scale-up but the commercial ethanol industry is currently, at least, sticking with *Saccharomyces cerevisiae*. For example, even though *Z. mobilis* has a higher ethanol yield on starch, all commercial producers continue to ferment starch using yeast. This seems to have a lot to do with the scale of production, for which yeast is particularly well proven and because of the difficulty of avoiding contaminations when working with bacteria (Dien, Cotta et al., 2003).

BBSRC has a programme of research developing microorganisms that can better ferment the sugars released in degradation of biomass.

<http://www.bsbec.bbsrc.ac.uk/programmes/lignocellulosic-conversion-to-bioethanol.html>

### Biomethanol, MTBE and Biomethane

Methanol (also known as wood alcohol) is produced by a process using natural gas as a feedstock and has similar physical and chemical properties to ethanol. Biogas can be generated from plants that produce methane gas sustainably along with carbon dioxide from plant biomass, which may come from organic household or industrial waste or from specially grown energy plants (Yadvika, Sreekrishnan et al., 2004).

Substrate can be manure from farm animals such as cows, pigs, chickens and horses; fat from slaughter waste or frying oil; organic household or garden waste; or municipal solid waste and rotten foodstuff. Organic waste from hospitals containing paper and cotton, municipal sewage sludge, waste from agriculture or food production, organic-rich industrial waste water etc., can also be used as consumable substrate. Often, energy crops such as maize (whole plant including the corn), clover, grass, young poplar and willow are especially grown for biogas production and added purely or in mixture (Antoni, Zverlov et al., 2007).

Anaerobic microorganisms typically produce biogas in a three stage process:

1. hydrolysis of the sugars (starch, cellulose, hemicellulose etc.), proteins and fats into sugars, fatty acids

and glycerol. This is followed by acidogenesis, the fermentation of these products into mainly acetic, propionic and butyric acid, carbon dioxide and hydrogen, alcohols and other minor compounds;

2. acetogenesis: the production of acetic acid and carbon dioxide
3. methanogenesis with up to 70% CH<sub>4</sub> and 30% CO<sub>2</sub>

It has been argued that biomethanol is preferably to bioethanol on the basis of thermal efficiency, carbon conversion and environmental burden<sup>9</sup> (Hasegawa, Yokoyama et al., 2010). Methanol is already used a fuel: for example, it has been used in the USA as a fuel in certain vehicles (e.g. race cars) either neat (100%) or blended since the 1970s (de Cerqueira Leite, 2004). Methanol can be used to make methyl tertiary-butyl ether (MTBE), an oxygenate that is blended with gasoline to enhance octane and create cleaner burning fuel. MTBE production and use has declined in recent years because it has been found to contaminate ground water (Antoni, Zverlov et al., 2007).

### Biobutanol

n-Butanol is already commercially used as a solvent and is mostly produced via chemical synthesis. The dominant synthetic process in industry, the acetaldehyde method, relies on propylene derived from petroleum (Wackett, 2008). Several companies, including British Petroleum and DuPont, are developing methods to utilize bacteria to produce n-butanol on a large scale for fuel<sup>10</sup>. Microorganisms capable of producing n-butanol by fermentation are *Clostridium acetobutylicum*, *C. beijerinckii*, and *C. tetanomorphum*<sup>11</sup>.

Butanol has a number of advantages over ethanol, especially in terms of transport. As a fuel mixture, butanol is more easily transported with gasoline and diesel through pipelines because of its lower tendency to separate from the fuel when contaminated with water<sup>12</sup> (Schwarz and Gapes, 2006). Butanol has two more carbons than ethanol, which results in an energy content about 40% greater. The octane number of butanol is 96, which is somewhat lower than that of ethanol but is still comparable to that of gasoline (91–99). Butanol also contains 22% more oxygen than ethanol making it a cleaner burning fuel (Qureshi, Saha et al., 2010). It was demonstrated in 2006 that n-butanol can

<sup>9</sup> except electrical energy consumption

<sup>10</sup> Chase, R. "DuPont, BP join to make butanol." USA TODAY. 30 June 2006

<sup>11</sup> [https://www.biofuelsdatabase.org/wiki/index.php5/N-Butanol\\_Pathway#References](https://www.biofuelsdatabase.org/wiki/index.php5/N-Butanol_Pathway#References)

<sup>12</sup> [http://blogs.princeton.edu/chm333/f2006/biomass/bioethanol/06\\_major\\_issue\\_biobutanol](http://blogs.princeton.edu/chm333/f2006/biomass/bioethanol/06_major_issue_biobutanol)

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be used either 100% in unmodified 4-cycle ignition engines or blended up to at least 30% (70% diesel) in a diesel compression engine or to 20% (80% kerosene) in a jet turbine engine (Antoni, Zverlov et al., 2007).

Historically, butanol has been produced biologically using *Clostridium acetobutylicum* because of its acetone–butanol–ethanol (ABE) fermentation capability. There are a number of Clostridia that can produce ABE (where butanol is the larger product in the ratio) and recent research has begun to more thoroughly explore the use of *C. beijerinckii*.

Clostridia fermentation has several limitations, including low titer, yield and productivity and improvements in the performance of the clostridia are necessary to move biobutanol fermentation research to a competitive commercial position. Efforts have been made in this direction using traditional biological engineering techniques (anti-sense RNA) through downregulation (Tummala, Welker et al., 2003) or over-expression (Tummala, Junne et al., 2003), which has improved ethanol production. There are also improvements being made in butanol output: *C. beijerinckii* BA101 is a genetically modified, hyper butanol producing strain, which produces at least 100% more butanol per litre glucose fermentation than did its parent strain (Formanek, Mackie et al., 1997). It can utilise a number of the sugars present in lignocellulosic biomass, for example arabinose, glucose, mannose and xylose (Ezeji, T, Qureshi et al., 2007). Other contenders include *C. beijerinckii* P260 (Qureshi, Saha et al., 2010).

A significant problem for butanol production via microorganisms, as was the case for ethanol production, is the toxicity of the solvents produced (the butanol and ethanol are toxic), creating their own limiting factor in their production. Whilst yeast and *Z. mobilis* are already reasonably tolerant to ethanol and have well understood fermentation pathways, the clostridia strains that produce ABE are far more sensitive to butanol. The stress response mechanisms used by these bacteria in response to increasing butanol concentration are not thoroughly understood, though progress is being made (Ezeji, Thaddeus, Milne et al., 2010). An important deficit exists for work with these bacteria in terms of extant genetic techniques (Zheng, Li et al., 2009). While progress is being made, this is at a slower pace than would be desirable. However, a recent report (Higashide et al. 2011) describes the use of a *Clostridium cellulolyticum* strain for isobutanol synthesis directly from cellulose without requiring a pre-treatment stage.

In order to improve butanol output, simultaneous fermentation and product removal techniques have been developed, including adsorption, liquid–liquid extraction, perstraction, reverse osmosis, pervaporation and gas stripping (Zheng, Li et al., 2009), with gas stripping seemingly the most promising method of improving butanol recovery.

The alternative to using these native species of *clostridia* (as with ethanol) is to engineer their genes into model species such as *E. coli* or *S. cerevisiae*. One such study (Atsumi, Cann et al., 2008) showed titers of up to 552 mg/l could be obtained (an improvement on the more common titers in clostridia of around ~20mg/l). Furthermore, unlike the pathway in *acetobutylicum*, the *E. coli* strain did not produce acetone, which in the production of n-butanol for biofuel is an unwanted metabolite. This remains significantly less efficient and productive than ethanol output from yeast (*S. cerevisiae*): much more genetic work must be done in improving use of genes from *clostridia* in *E.coli*.

BBSRC has a programme of research investigating synthetic biological processes that might produce bacterial strains better able to convert lignocellulose into fermentable sugars and thus to butanol. The research aims to test the best strains on an industrial scale.

<http://www.bsbec.bbsrc.ac.uk/programmes/second-generation-sustainable-bacterial-biofuels.html>

## Biohydrogen

The production of hydrogen by microorganisms was originally observed in 1896 but work on the microbial mechanism of hydrogen production really only began in the 1940s (Prince and Kheshgi, 2005). Today, the production of hydrogen from bacterial or algal fermentation is still seen as an ideal fuel for use in transportation systems. Its major benefits are that it can be converted into electrical energy in fuel cells or can be combusted into mechanical energy without producing CO<sub>2</sub> (Antoni, Zverlov et al., 2007). Three kinds of bacteria can produce hydrogen: cyanobacteria, anaerobic bacteria and fermentative bacteria (Demirbas, 2009: V). Cyanobacteria, for instance, can produce hydrogen using two kinds of enzymes: nitrogenases and hydrogenases. There are a number of complications in the production of hydrogen using photosynthetic energy (i.e. by using sunlight) that have yet to be fully understood, although significant progress has been made with understanding the molecular pathways in photosynthesis. There will also be challenges associated with the scaling-up into industrial

processes and the engineering that will have to go into creating an effective photobioreactor (Prince and Kheshgi, 2005). Microbiological hydrogen production is not yet developed into an economically viable technology, and hydrogen production is lagging behind expectations.

### Biodiesel (FAME and FAEE)/Microdiesel

Fatty acid methyl esters (FAME) are one of the fatty acid esters generically referred to as biodiesel, which is increasingly lauded as a future bioenergy source since it is seen as being a much cleaner, renewable source of energy compared to petrodiesel. The fuel properties of FAME depend on the plant or animal oil source of the triglyceride (three-fat molecules) (Knothe, 2005). In Europe, diesel fuel is required to be blended with biodiesel and blends up to 20% fatty acid ester (biodiesel) do not require engine modifications. Biodiesel can be legally blended with petroleum diesel in any percentage. The percentages are designated as B20 for a blend containing 20% biodiesel and 80% petroleum diesel, B100 for 100% biodiesel, and so forth. In January 2011, the US Department of Energy announced a conditional \$241 million loan guarantee for Diamond Green Diesel, LLC, a proposed joint venture between Valero Energy Corporation and Darling International Inc., for an industrial scale plant to produce biodiesel primarily from waste animal fats.

Biodiesel is generally produced by treating the oil with methanol over an alkali catalyst (Ribeiro, Pinto et al., 2007), although a variety of other processes are under investigation (Andrade et al. 2011). The source of the oil varies from region to region. In the US, soybean is the plant source of choice. A biochemical method of producing FAME from triglycerides involves an enzymatic transesterification employing lipase derived from *Candida antarctica* (Köse, Tüter et al., 2002).

The potential sources for the oils for conversion are primarily: vegetable oil; animal fats; and recycled grease from waste (Tyson, Bozell et al., 2004). Vegetable oil comes from seeds (which are crushed to produce crude oil that can be filtered, refined, etc.). Animal fats come from greases, meat, blood, feathers and such, produced in slaughter houses. Recycled grease comes from cooking oils from restaurants and food processors. Currently, biodiesel production uses plant oils for the vast majority of its starting material (Fortman, Chhabra et al., 2008).

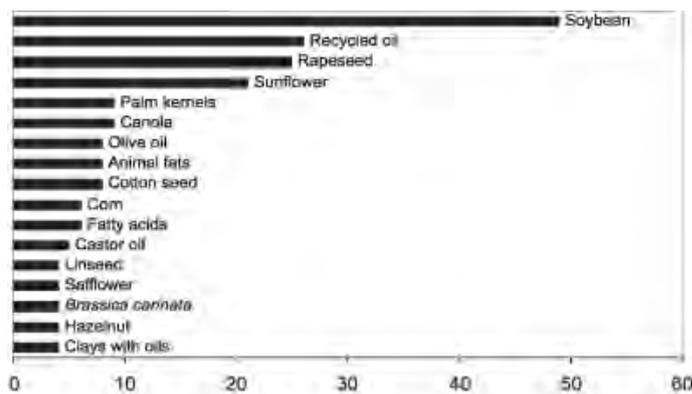


Figure 4. Leading biodiesel sources cited in scientific articles.

Figure taken from (Pinto, Guarieiro et al., 2005)

Overall biodiesel production in the EU27 has increased, reaching 7.7 million metric tonnes (2.75bn US gallons) in 2008, an increase of 35.7% from the 2007 figures. Biodiesel production in the United States also increased in the past decade from two million gallons in 2000 to 250 million gallons in 2006 with an estimated of 450 million gallons being produced in 2007. According to the National Biodiesel Board, there are 105 plants in operation as of early 2007 with an annual production capacity of 864 million gallons (Li, Du et al., 2008).

An alternative biodiesel is Fatty Acid Ethyl Esters (FAEE), which are less commonly produced industrially than FAME because they require ethanol for their production and methanol is cheaper and more abundant than ethanol (Fukuda, Kondo et al., 2001). The most common industrial method of FAEE production is via chemical catalysis driven by alkali, however an acid catalyst may also be used. FAEE can be produced via bacteria, specifically *Chromobacterium viscosum* (Shah, Sharma et al., 2004). Again, genetic engineering of the source of oils could eventually lead to a fuel enriched with certain fatty acids, ideally oleic acid, which exhibits a combination of improved fuel properties (Knothe, 2005).

Bacteria and other microorganisms may in the future have a much more foundational role in the production of biodiesel by being biomass themselves. Possible sources include: autotrophic microalgae; heterotrophic microalgae; yeast; and bacteria.

Autotrophic microalgae can utilize carbon dioxide as the carbon sources and sunlight as the energy for oil accumulation under some special conditions. It has been

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found that many autotrophic microalgae, such as *Chlorella vulgaris*, *Botryococcus braunii*, or *Navicula pelliculosa*, can accumulate oils (Chisti, 2007; Li, Du et al., 2008). By altering the cultivation conditions or using genetic engineering some autotrophic microalgae can be converted to heterotrophic microalgae. These microalgae can accumulate oils using organic carbon as the carbon source instead of sunlight, which could be significantly cheaper (Xu, Miao et al., 2006). For example, via this conversion into heterotrophy *Chlorella potothecoides* accumulated oil content about four times greater than that in the corresponding autotrophic cells (Xiao-Ling and Qing-Yu, 2004).

Many yeast species, such as *Cryptococcus albidus* and *Lipomyces lipofera* have been found to be able to accumulate oils under specific cultivation conditions, and it was reported that different yeast species led to different oil accumulation (Li, Du et al., 2008). The main fatty acids in yeast oils were myristic acid, palmitic acid, stearic acid, oleic acid, linoleic acid, and linolenic acid. Such yeast oils might be used as oil feedstocks for biodiesel production (Liu and Zhao, 2007).

Very few bacteria can produce oils capable of being used as the feedstock for biodiesel production (Liu and Zhao, 2007). Therefore, bacteria are mainly used to produce specific-use lipids (rather than generic fuel use), such as polyunsaturated fatty acids and some branched-chain fatty acids (Patnayak and Sree, 2005), but it has been shown that *Gordonia* and *R. opacus* could accumulate oils under some special conditions with maximum oil content of 80%, but the biomass is rather low at only 1.88 g/l (Gouda, Omar et al., 2008). However, compared to other microorganisms, the fatty acid synthesis pathways of bacteria, particularly model bacteria, are well-understood (Wentzel, Ellingsen et al., 2007) and (Alvarez and Steinbüchel, 2002). As such, genetic engineering to modify a bacterium to improve its oil accumulation seems quite feasible. For example, it was reported that a metabolically engineered *Escherichia coli* could produce biodiesel (fatty acid esters) directly, and the fatty acid esters concentration of 1.28 g/l was achieved by batch fermentation using renewable carbon sources (Kalscheuer, Stolting et al., 2006).

The major benefit of microbes over plants and other sources of oil is the massive reduction in the land requirement and thus the elimination of the food competition problem (Chisti, 2007). This microbial strategy for production of biodiesel usually means the product is called microdiesel (Kalscheuer, Stolting et al., 2006).

## Isoprenoids

The isoprenoids are a large family of hydrocarbon molecules that are synthesized with the use of the activated hydrocarbon monomers isoprenyl pyrophosphate (IPP) and its isomer dimethylallyl pyrophosphate (DMAPP) (Kuzuyama, 2002). It is possible to produce several branched-chain alcohols, alkanes, alkenes and cyclic hydrocarbons through the isoprenoid biosynthetic pathway, which makes the microorganisms (e.g. the algae *B. braunii*) that produce them a promising biofuel source (Wake and Hillen, 1980; Metzger and Largeau, 2005). The oils (hydrocarbons) produced by these microorganisms are a complex mixture and thus would be more a crude oil that would require hydrogenation and cracking (as traditional crude oil does) (Tsukahara and Sawayama, 2005). The source of the energy and substance of the oils in the study above was sewerage (Tsukahara and Sawayama, 2005).

Rather than working with the natural producers of IPP (and by extension the hydrocarbons) the research has begun to engineer the pathways responsible for this conversion process into model organisms such as *E. coli* (Martin, Pitera et al., 2003; Yoon, Park et al., 2007) and *S. cerevisiae* (Ro, Paradise et al., 2006). Recently, improvements have been made in both those model systems' use of the IPP production pathway (Pitera, Paddon et al., 2007; Shiba, Paradise et al., 2007). Despite some improvements the yield remains quite low (Ro, Paradise et al., 2006). A further possibility of this pathway is its use to produce isopentanol and isoamylacetate, both of which are fuel additives (Hull, Golubkov et al., 2006). For example, researchers have demonstrated that a pyrophosphatase isolated from *Bacillus subtilis* can modify IPP to form isopentenol (Withers, Gottlieb et al., 2007) and a similar pathway has been engineered into *E. coli* (Horton, Huang et al., 2003).

## Web Resources

The following websites are useful in finding out more about biofuels and could be used a resource to keep updated with the developments in biofuel science. These links might be provided to workshop participants to provide them with a means to further engage with biofuels science, policy and other issues.

### European Biofuels Technology Platform

<http://www.biofuelstp.eu/index.html>

This website contains lots of information about and reports on the scientific, policy and economic issues associated with biofuels production in the EU.

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## **BioMatNet**

<http://www.biomatnet.org/home.html>

A website providing information about and links to many of the biofuels projects funded in the EU over the last 20 years. Links to reports are not always clear, but look for the little Adobe pdf icon.

## **Refuel**

<http://www.refuel.eu/biofuels/biodiesel/>

The Refuel project is orchestrated by a group of academic and industrial partners that seek to encourage a greater market penetration for biofuels so as to meet EU biofuel targets. It contains information on a number of biofuels and has links to publications on how Refuel thinks EU targets might be met.

## **European Biodiesel Board**

<http://www.ebb-eu.org/>

A website run by the non-profit organisation, EBB, which consists of many corporations seeking to increase the use of biodiesel in the EU.

## **Biofuels Digest**

<http://biofuelsdigest.com/bdigest/category/research/>

A website that brings daily news about biofuels policy, science, economics, industry, etcetera. One page that is particularly useful for keeping up with scientific developments is linked above.

Or an alternative news source is: Biofuel.org.uk <http://www.biofuel.org.uk/biofuel-news.html>

## **US Department of Energy Biomass Program**

<http://www1.eere.energy.gov/biomass/index.html>

The DoE's website on Biomass contains a range of resources for different audiences, including the following list of resources [http://www1.eere.energy.gov/biomass/information\\_resources.html](http://www1.eere.energy.gov/biomass/information_resources.html) targeted to particular types of reader from industrialists through academics to school children.

## **Crop Biotech Update**

<http://www.isaaa.org/kc/cropbiotechupdate>

This is a weekly newsletter, with a fortnightly supplement on biofuels, produced by the International Service for the Acquisition of Agri-Biotech Applications (ISAAA), an global non-profit network supported by a range of partners including universities, industry and international organizations.

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## Chapter 4 Contexts for Bioenergy

As we explained in Chapter 1, the future for bioenergy does not depend solely on the development of the technology itself, which we reviewed in the previous chapter. The pathway to adoption is also shaped by a context that includes the fate of competing technologies, the influence of climatic and environmental factors on energy demand and the capacity to meet this from plants, the economic resources available for investment and the decisions on where they should be directed, the growth of population and the choices made by people about where to live, and the value choices that people make about landscape, mobility, personal energy consumption and the importance of the future relative to the present. There is, in principle, an almost infinite range of contextual factors that could be considered. However, we have tried to constrain these and to give a reasonable selection of relevant evidence on each, although this is inevitably a more limited exercise than has been possible with the technology review. As before, we shall conclude by noting some web sites that facilitators could consult to update what has been said here and ensure that scenarios reflect the most recent available evidence.

### Context

#### Competing Energy Technologies

It is important to remember that the development of bioenergy technologies may be driven as much by the demand for alternatives to hydrocarbons as chemical feedstocks as by the search for biofuels: indeed there are analysts who argue that this may be a more important driver, although noting the potential for fuels, like biodiesel, that slot easily into existing engine and supply chain technologies (Lux Research 2010). The future for biofuels will equally be shaped by the development of other energy technologies that do not require the use of fossil fuels or which use them more efficiently (Accenture 2009) (Energy Research Partnership 2010). Fossil fuel consumption may also be reduced by reduction in demand, resulting from, for instance, improvements in building design and insulation or teleworking, although there are suggestions that reductions in traffic may be outweighed by higher energy consumption in other locations (Banister, Newson, and Ledbury 2007). In practice, most competing fuel technologies contribute to the generation of electricity, which is then a source-neutral means of transmitting energy to the end-user (Department of Energy and Climate Change 2010).

Biomass may have a contribution here as material to be burnt in power stations, possibly in combination with fossil fuels, but the size of this contribution will reflect its cost and security of supply relative to other sources, and the relative amount of R&D investment directed towards each (Committee on Climate Change 2010). No single technology has established itself as a unique candidate for replacing fossil fuels so that it will be necessary to follow multiple innovation pathways (Consortium for Science, Policy and Outcomes 2010). These include (onshore and offshore) wind; hydro; tide; wave; geothermal; and solar. In the UK, some of these – hydro, tide, geothermal – offer relatively secure and stable generating capacity, while others – wind, wave, solar – are more intermittent and require some measure of back-up capacity, such as nuclear, to ensure continuity of supply, unless there are significant technological developments in storage technology. Solid or liquid biomass products could be storable for this kind of reserve use without major innovation. Gaseous biomass products, to which may be added landfill and sewage gas as closely related sources, present more of a storage challenge, although the gas could be liquefied or pumped into underground reservoirs depleted by natural gas extraction. UK-originated biomass has been estimated as capable of contributing around 10% of current primary energy demand by 2030, mainly from organic municipal waste, sewage sludge and waste wood (E4Tech 2009).

Few people are currently arguing that biofuels will have a major role in large-scale power generation. They could, however, plausibly have a place in more distributed generation systems as a local source of easily storable back-up capacity or as an alternative to existing fossil fuels in off-grid locations, replacing diesel for domestic generation, for example. The key contest seems more likely to occur in transport applications, where liquid fuels are currently dominant and, in some applications, not substitutable. Even here, biofuels will contest the market with source-neutral electricity in battery-powered vehicles and with hydrogen, whether used directly in internal combustion engines or through fuel cells (Zah et al. 2010). Battery-powered vehicles face current constraints from the availability of lithium, unless new chemical bases are developed: some analysts question whether sufficient can be mined to sustain the number of cars presently in use, let alone allowing for expansion in demand from developing countries (Tahil

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2006)(Meridian International Research 2008). Others are more sanguine, pointing out that lithium in batteries can be effectively recycled (Evans 2008)(Haber 2010). Hydrogen fuel cells still face important cost barriers and require substantial investment to create production and supply networks (International Partnership for Hydrogen and Fuel Cells in the Economy 2010). Biomass could be one source of hydrogen production through microbial action (Das and Veziroglu 2001). Overall, however, there is some scepticism about the extent to which electric vehicles in any form can be competitive without extensive subsidy or regulatory intervention (Lux Research 2009). There are certainly niches where liquid fuels that closely resemble existing technology are likely to be dominant through to 2030 and well beyond (Department of Energy and Climate Change 2010). Aviation is one of these (Air Transport Action Group 2009), as are agriculture and other primary industries such as mining and quarrying, together with heavy long-distance haulage and some specialized types of industrial heating. Biofuels that closely resemble kerosene and diesel are likely to be the principal contributors to meeting energy demand from these sectors.

## Climate and Environment

### Climate:

Reference has been made at a number of points to the importance of climate change as a potential influence on both technology and socio-economic dimensions. Climate change will affect both the supply of bioenergy sources for conversion to biofuels and the demand for fuel. Biofuels may well make a contribution to reducing carbon emissions, although, at least for ethanol, studies show that this is not a large effect (Marland and Turhollow 1991) and others suggest that it may be outweighed by the carbon generated from land clearance (Righelato and Spracklen 2007). However, it must also be recognized that the case for developing biofuels does not necessarily rest on climate change alone. Biomass has the potential to make a significant contribution to dealing with the consequences of the depletion of accessible oil resources, and the subsequent competition between uses of oil as a feedstock and oil as a fuel. Biomass could contribute to either use, depending on the investment decisions that are taken over the next few years. In other words, the argument for developing biofuels is not necessarily a Green one: they can as equally be considered as an attempt to develop a substitute and price competitor for oil- and petroleum products in order

to sustain patterns of both fuel and chemical production broadly along present-day lines.

### Projections

It is not often acknowledged that, considered purely in national terms, climate change is not necessarily bad news for much of the UK, because of the buffering it experiences from the sea compared with the impact on other parts of Europe (DEFRA 2010). This depends to some extent on assumptions about ocean currents, like the Gulf Stream, although concern that the melting of the Greenland ice shelf will turn this off seems to have declined since it was first expressed and DEFRA advisers think it unlikely to be relevant before 2100 (DEFRA 2010). Even if this were the case, the seas around the UK would still represent a powerful heat sink, tending to moderate both summer and winter temperatures, particularly to the north and west of the UK. Sea level rises would be a concern in some areas, but many of these have already been identified as indefensible from coastal erosion and incursion anyway. Climate change would be more of a challenge to the southeast, where summers would become hotter and where the lack of water might become a significant problem for both agriculture and urban development. However, some production will be suited to the change: major champagne producers are reported to have been buying land in Kent and Sussex because the future conditions are thought likely to replicate those currently experienced in their home region (BBC 2004).

The serious problems arise when we consider the UK in a wider context and the difficulties that might be experienced if we were to be an island of relatively benign conditions in a world that experienced more difficulty. This might, for example, lead to intense long-distance migration pressures of the kind that are currently being experienced in Mediterranean Europe, in the face of which the English Channel has already proven to be a somewhat porous barrier. These may be intensified by within-EU migration from areas like southern Spain and France, where substantial areas may become desertified and experience summer temperatures approaching 50°C (Alcamo et al. 2007). These changes will also have significant implications for patterns of agriculture, within Europe and globally, which will, in turn, create different market pressures on UK agriculture and food supply.

Climate change is also likely to impact on the demand for energy, although not necessarily in ways that are specific to biofuels. Hotter summers will generate more demand for air

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conditioning and refrigeration, adding new summer peaks to established seasonal patterns. Extreme winter events will continue to create spikes in demand but not in ways that are qualitatively different from present-day cycles (De Cian, Lanzi, and Roson 2007). The main challenge is likely to be to the resilience of energy systems rather than to their specific sources of fuel.

Although there are contrary views (Forum for the Future 2008), climate change is not likely to be a major factor through to 2030. The IPCC projections show little divergence between the possible pathways to 2100 because the drivers for the next 20 years are already in the system (Intergovernmental Panel on Climate Change 2007). (Intergovernmental Panel on Climate Change 2007)(Intergovernmental Panel on Climate Change 2007) The issue for scenario authors is more one of the extent to which measures are likely to have been taken by 2030 in anticipation of developments beyond that date, in the hope of managing the planet onto one of the lower increase pathways to 2100 (Kemp and Wexler 2010) (URS Corporation 2010).

#### **Environment:**

Land is a limited resource and bioenergy crops take up a large amount of land. If half of the crops needed to meet the UK's five per cent renewable transport target (by 2010) were grown in the UK, 740,000 hectares of land would be needed (Environment Agency 2007). By 2010 up to 800,000 hectares could be available in the UK for bio-energy crops (European Environment Agency 2006). This 'available' land includes all land set-aside and a significant area released from food and fodder production (CONCAWE Ad Hoc Group on Alternative Fuels 2002). Replacing set-aside land could lead to loss of habitat and damage biodiversity.

Across the EU, 14 million hectares of land would be needed to meet the 5.75 per cent target in 2010 (IFP 2007), but there is only 13 million hectares of arable land available (European Environment Agency 2006). It is therefore highly unlikely that the EU would aim to meet its target just from EU crops, and imports are likely to play a large role.

The growing demand for biofuel feedstock is likely to increase environmental pressures in countries outside the EU. Increasing demand for palm oil is already leading to large tracts of rainforest being cleared in Malaysia and Indonesia. This has largely been for vegetable oil for western food markets, but is increasingly being used for cheap oil as a renewable fuel (Commission of the European

Communities 2006). Destroying rainforest would cause loss of biodiversity and habitat in the producing country, as well as cancelling out any carbon savings. On the other hand, it has been suggested that biofuel production on land marginalized by climate change could make an important contribution to sustainability in Australia, creating opportunities for rural employment and producing biodiesel close to sources of demand in mining and agriculture (Odeh, Tan, and Ancev 2011).

Producing biofuels can also affect water use, water quality, waste management, and soil fertility. Some crops increase the risk of reduced recharge to groundwater aquifers (DEFRA 2007a), and overusing chemicals pollutes groundwater and rivers (Commission of the European Communities 2006). Using new land for arable production can release CO<sub>2</sub> (CONCAWE Ad Hoc Group on Alternative Fuels 2002) and increase the risk of nitrate leaching. Feedstocks for second-generation fuels such as miscanthus, linseed, grass, switchgrass, and willow have fewer effects on the environment than those currently ready to market (DEFRA 2007b), (European Environment Agency 2006). However, concern has been expressed about the potential implications of apparently low-impact technologies, like algae, which require relatively little land but may make heavy demands on water supplies require chemicals that could contaminate discharges (Ryan 2009). Food supply modelling is still struggling with the limitations of available datasets but does not currently suggest that there is a serious risk of a global Malthusian crisis, where population growth exceeds food supply, over the time period being reviewed (Godfray et al. 2010) (Reilly and Willenbockel 2010). Locally, though, there are acknowledged risks of potential problems because of competition for land and, especially, water, that may have implications for food security (de Fraiture, Giordano, and Y Liao 2008)(Committee on Water Implications of Biofuels Production in the United States 2008).

#### **Socio-Economic**

Social scientists typically deal with problems of complexity by focussing on one major variable and seeing everything else as secondary: economists think everything is to do with the allocation of scarce resources; geographers, the allocation of space; anthropologists, with culture and values; psychologists with personality, attitudes and cognition, etc. However, this specialization is a handicap in constructing and discussing scenarios because, as we noted earlier,

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these need to capture systems as a whole rather than emphasising one dimension over another. At the same time, some simplification is essential if any progress is to be made in thinking with scenarios in the context of dialogue and engagement. We cannot have a scenario of everything – but we need a scenario that contains enough to be realistic and plausible. In this document, then, we have selected four socio-economic dimensions that seem to us to be essential components of any scenario, particularly as they are likely to influence the market for biofuels. Having introduced these, however, we shall then discuss some of their interactions and the way these may have indirect effects on the supply and demand for biofuels. We shall then place them into the context of global socio-economic systems and use this as a bridge into discussion of the potential impact of climate change as a global process with specific implications for the UK. The four dimensions that we have identified are Economy; Demography; Location; and Culture.

#### **Economic:**

Economic activity is one of the major drivers for energy demand. Other things being equal, an active economy will use more energy for manufacturing, transport and domestic purposes than will a stagnant one. Factories operate for longer periods at higher levels of production, while citizens travel more for both business and leisure and use more energy for domestic amenity. The present context is one of great uncertainty about the likely course of economic activity during the next five to ten years, which will, in turn, frame the possibilities through to 2030. Scenarios need to reflect this. On the one hand, there are economists who argue that the present government's policy of deep and rapid cuts in public spending, including capital investment and research and development, will lead to a short hiatus in economic growth which will then pick up on a more dynamic course led by the private sector (Bank of England 2011). This may lead to some delays in energy investments but will not fundamentally constrain developments over the next twenty years. On the other hand, there are also economists who argue that these cuts will check growth to such an extent that the UK will slide into a period of stagnation comparable with that of Japan in the 1990s (Callen and Ostry 2003) (Posen 2010). This could mean a 'lost decade' of investment that would lead to a significant infrastructure and skills gap by 2030 (Bank of England 2010).

Over the longer term, economic growth is also affected by population trends, discussed in the next section. This could represent a difference between an annual average growth

rate of 2.1 per cent and one of 2.4 per cent through to 2030, depending on whether reproduction and migration increase to generate faster growth. If we take 2010 as a baseline, then there would be a 6 per cent difference in GDP by 2030, depending on the pathway. This may not sound a large amount but it is roughly the projected cost of state pensions in that year (Office for Budgetary Responsibility 2011).

The prospects for the UK economy are closely linked to those of the global economy, particularly our major trading partners in Europe and the so-called BRIC (Brazil, Russia, India, China) countries with their rapid rate of development. Faster growth elsewhere could aggravate the UK's problems by draining the bioenergy sector of skills and capital or it could create an expanding private market that facilitates export-led growth, producing a revenue stream for further investment, and retaining skills in the country.

At this point, it is not possible to take a view on which pathway is more likely and scenario exercises should incorporate both low and high growth alternatives in an even-handed fashion.

#### **Demographic:**

Energy demand will also be affected by the size and structure of the UK population – the number of potential energy users, which is not wholly independent of either the economic or the climate change dimensions. ONS projections suggest that the total UK population is likely to lie within a range from 67 to 75 million by 2030, with a principal projection of just over 70 million, compared with a current population of about 61 million (Office of National Statistics 2009). During this period, the population will also age, with about 23 per cent being over 65 by 2033 compared with 16 per cent in 2008. Population growth reflects an interaction between the number of live births, itself influenced by the number of women of reproductive age and their intentions, the number of deaths, influenced by environment, lifestyle and medical care, and net migration, the balance between inflow and outflow (Mitchell and Pain 2003). On a low economic growth pathway, population is likely to grow more slowly: women have fewer children, mortality rates decline more slowly and net migration tends to be small or even negative. On a high growth pathway, the converse is likely to be true.

However, this may be affected by global factors. As we shall note, the UK may be a favoured location if climate change accelerates, although this is unlikely to have a strong

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impact by 2030. Migration rates may, then, be influenced by climate change elsewhere, creating difficulties for citizens and residents in countries that are more adversely affected that push them to seek to move towards the UK. By 2030, this may be more a question of pressures from outside on the EU as a whole, but some climate projections suggest that parts of Southern Europe may not be sustainable places to live over a longer period and that we may expect to see migration pressure from these zones on more northerly parts of the EU. If these considerations become substantial, we could see a flat UK economy with more substantial population growth from climate refugees, depending upon EU and UK immigration policy. Here, demography and economy would interact with culture and the value placed on free movements across national borders.

We must also take account of the implications of an ageing population. Current projections suggest that the number of households in England is likely to grow by 27 per cent between 2008 and 2033, with two-thirds of the increase accounted for by single-person households. By 2033, 19 per cent of the English population will live alone, compared with 14 per cent in 2008, and 33 per cent of household heads will be over 65, compared with 26 per cent in 2008 (Department of Communities and Local Government 2010). (Trends are similar in the other nations of the UK but differences in methodology mean their projections are not easily aggregated.) An increase in the number of households implies an increase in domestic energy demand simply because space heating, cooking, and transport do not decline proportionately to the number of people in a household. Arguably, too, older people may have greater requirements for space heating, particularly if they are at home much of the day, although this could be influenced by low economic growth leading to fuel poverty because older people are unable to purchase as much energy as they would like or as might be considered optimal from a health point of view. We might also infer from this trend that there may be an increased transport demand from carers, whether kin or paid. Care services that go to old people living alone will generate fuel demands, as, potentially, will journeys by kin to sustain relationships or to cover for limitations in public or private care services, or in access to them, which may also be aggravated by low economic growth. There may also be an impact on migration in that the ratio between the working and the pensionable population, which is projected to fall from 3.2 to 2.8 between 2008 and 2033, even allowing for the previous

government's plans to raise retirement ages (Office of National Statistics 2009). These economically active adults cannot simultaneously be employed in manufacturing and in care work, whether paid or unpaid. There is already a heavy dependence on migrant labour in the paid care sector and this seems unlikely to decline, unless there are major changes in immigration policy and employment preferences among the home population. Other European countries will face the same problem in more acute forms: the average ratio between the working and the pensionable population for the EU as a whole is expected to be about 2.5 to 1 by 2030, heading towards 1:1 in many countries, although not the UK, by 2050. This is likely to depress the prospects for economic growth within Europe, with the potential GDP for the EU15 – the pre-2004 member states – falling from 2.2% to 1.8% through to 2030 and for the EU10, the post-2004 members, from 4.3% to 3.0% (Economic Policy Committee and the European Commission (DG ECFIN) 2006).

Migration is also potentially a driver of international transport demand. Inward migrants may well wish to retain contact with their countries of origin. Outward migrants present a policy issue about the extent to which the UK government wishes to retain contacts with this diaspora by facilitating return transport to sustain relationships with family and professional associates. However, the issue is less one of whether the net balance is inward or outward than of the volume of migration and whether it is primarily within the EU or involves longer distance movements. If migration is primarily within Europe, there could be some substitution of surface for air travel, which would have implications for the balance of demand between liquid biofuels suitable for aviation use and biofuels suitable for electricity generation, powering long-distance rail services, or for long-distance road transport, which is unlikely to be provided by current battery technologies. Shorter term movements should also be acknowledged. On the timescale here, it is unlikely that there will be major shifts in tourism patterns within Europe, although, over a longer period, hotter summers and a degree of desertification in traditional Mediterranean destinations may make the more equable UK climate look a more attractive destination for vacation travel.

Scenario exercises need to be able to reflect both high and low UK population estimates and high and low rates of mobility. However, the ageing of the population should be treated as a constant feature under any scenario, together with its implications for household size.

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**Location:**

Although UK land use planning has generally produced higher residential densities, and less suburban sprawl, than in North America or Australia, facilitating the sustainable use of public transport (Williams 2009), it has struggled to contain the emergence of long-distance commuting from rural areas and market towns into cities, particularly in the South East of the country (Frost 2006). While there has been some re-population of central London, in contrast to the continuing declines experienced by many of the older industrial cities, the most rapid population growth has occurred in areas like Northamptonshire and Oxfordshire, where it is difficult to design public transport alternatives to the use of cars for some part or the whole of many commuting journeys, and where those journeys may be too long for batteries to make a significant contribution to fuel demand. Although tele-working has been seen as a magic solution to this problem for many years, it has failed to take off on any scale sufficient to have an impact on the problem (Geels and Smit 2000). At best, it seems to be making a marginal contribution and, in fact, may have the effect of increasing travel demand by facilitating working from many places 'on the move' rather than from a home base. This may be offset by reductions in energy demand at the office or workplace, but it is not clear whether these are outweighed by the extra domestic energy consumption required by home-based workers (Banister, Newson, and Ledbury 2007).

What may be more important, however, is internal migration. To the extent that economic opportunities are unevenly distributed within the UK, something which may be aggravated within either the high-growth or low-growth economic pathways, they are likely to generate additional transport demand, both towards areas offering employment opportunities and in return to maintain family and other networks. While this may be manageable, in energy terms, by greater use of electrified rail services between major cities, the perceived affordability of this mode relative to private car use or long-distance buses may affect the balance between fuels for power generation and liquid fuels for transport purposes. It might also be suggested that the Coalition government's recently-announced changes to social security policies may have the effect of moving poorer households to peripheral areas of major cities, away from opportunities for low-paid employment in a range of service industries unless they can commute at unsocial hours when public transport options may be limited. These types of

journeys may be suitable for electric vehicles but uptake would depend on the capital cost for households who may typically buy quite old petrol cars.

Overall, it would be unwise for scenarios to assume that changes in location are likely to exert much influence on demand for biofuels, relative to other drivers. What may be more important is the implication that there will continue to be some level of liquid biofuel demand for transport markets that cannot be converted to other sources of energy, primarily electricity.

**Culture and Values:**

One of the hardest areas to incorporate in scenario design is any presumed shift in societal values over a relatively short period. It is a dimension where there are particular opportunities for wishful thinking and simplistic assumptions about the degree to which citizens will in fact voluntarily modify their behaviour to fit the assumptions of planners or lobbyists, whether on behalf of industry or Green NGOs. The leading environmental activist, Jonathon Porritt, for example, was reported to have argued at a meeting of the Optimum Population Trust in 2009 that measures should be introduced to reduce the UK population to 30 million in order to reduce its demands on planetary resources (Sunday Times, 22 March 2009). This would be achieved mainly by measures to influence women's reproductive choices intended to persuade UK-resident women never to have more than 2.0 children (Sunday Times, 1 February 2009). The OPT itself would supplement this by immigration controls and restrictions on social security payments to promote a sustainable UK population in its own terms of between 17 and 27 million people (Optimum Population Trust). The difficulties of managing migration by means of arbitrary caps have already been exposed by the current government's interim policy, although the OPT does concede that within-EU migration could be disregarded since environmental footprints do not vary much between member states and the results of these flows are largely self-cancelling. However, it is not clear that the barriers to reproductive choice in a country like the UK are so significant that policies like even greater availability of abortion, sterilization or long-acting contraception or withdrawal of social security and tax benefits for third and subsequent children would have more than a marginal impact at a collective level. Both Porritt and the OPT seem to assume that all pregnancies to teenagers are unwanted and should be prevented, which is certainly questionable. While the mean age at marriage has been rising steadily, and only

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about 4,000 people under the age of 20 were married during 2008 (ONS Marriage Summary Statistics 2009), two-thirds of births to women under 20 were registered in the name of both parents, which is conventionally taken as an indicator of stable cohabitation (Office of National Statistics 2010). In the absence of evidence that women who have more than two children are doing so against their will, voluntary strategies do not seem credible: population reduction would require more coercive actions, whether by community sanctions of shaming and exclusion or by direct state interventions similar to those employed through the controversial 'one-child' policy in China.

While scenarios should incorporate some recognition of a 'Deep-Green' Utopia inspired by the work of Arne Naess (Drengson and Inoue 1995) of a planet with 2 billion or fewer inhabitants – against the 7 billion or so today and the 9 billion projected for 2050, caution should be used in treating this as a plausible direction of travel by 2030, rather than as a way to explore reactions to the implications of such a way of life. Advocates of these outcomes tend to depict a world dominated by communitarian values, which favour village-scale communities, depending largely on their own local resources, with very limited travel and trading between them. Bioenergy may have a part to play in this sort of socio-economic system, but it is unlikely to require the technical complexity assumed by BBSRC investment. The main biofuels would be likely to come from coppicing and plant waste with little or no intermediate processing. In fact, it is not clear how this vision would sustain any level of technological complexity as in contemporary biofuels – and indeed wind or solar generation - because of the scale of trading and production networks involved. A community might build a windmill or a water wheel from local resources but it is improbable that either could reach the sophistication and efficiency of a contemporary wind- or water-turbine. It should also be noted that this vision does not have strong roots in any actual historical past society. Recent discoveries at Stonehenge, for example, have shown a surprising and unexpected degree of mobility as long ago as the Neolithic period, with the remains of humans from the Mediterranean being found in graves in Wiltshire (BBC News, 28 September 2010). Internal UK migration towards greater economic opportunities in the south and southeast of the country can be documented at least as far back as the thirteenth century (Clark 1979)(Razi 1993).

Scenarios should also recognize and give equal weight to a counter-utopia where markets are allowed free

play to allocate resources. There is actually rather better evidence for markets as drivers of social change than of communitarian experiments (Bowles 1998). The relationship between completed family size and level of economic development has long been recognized, for example (Galor and Weil 2000). Once children are no longer of value either for their labour power in primary industries or as a form of insurance against need in old age, fertility rates drop with remarkable speed. One of the major problems is the ability to incorporate uncertain long-run costs and externalities into contemporary prices, which is an argument for government intervention through taxation but not necessarily an argument against markets in themselves. In theory, market advocates would argue, a properly functioning market would send signals to consumers through the price mechanism that would influence their purchasing decisions in an environmentally sensitive fashion. In practice, of course, the outcomes may be different. More affluent citizens may simply decide to pay a higher price rather than change their behaviour. If I do not wish to experience the common carriage on public transport, I can continue to drive my SUV and park it at will, simply by effecting a marginal reduction in my discretionary spend elsewhere. Markets are also seen as more powerful drivers of innovation both to maximize those 'goods' sought by market actors and to minimize the 'bads' that they wish to avoid. The communitarian vision often has a very static quality as if nothing would ever change and nothing new would ever happen. However, there are also those who argue that the capitalist solution is simply unachievable: so much would have to change that the system would necessarily collapse, although this might take the form of technocratic feudalism, propped up by state power, rather than an eco-friendly mode of civilization. Such states, though, may decay from within, much as did the former Soviet Union because of the way the command structure diverts resources from innovation and productive investment (Leahy 2008)

The choice between a communitarian or a market future is not reducible to considerations of efficiency or effectiveness. It reflects prior commitments about what constitutes a good society, about what level of material comfort is considered appropriate and about what degree of personal autonomy is desirable. In reality, the future is likely to contain elements of both, but the use of pure types in scenario exercises may help to focus dialogue and engagement on the acceptable range of compromise.

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## Web resources

There are a very wide range of potential resources for updating this section and the following list is intended mainly as a starting point for searches. Within the UK, important responsibilities in this area are devolved to the various national governments and assemblies. This list concentrates on those covering the UK, with some English additions, but users in the other constituent nations should also consult the equivalent websites for organizations in their own part of the kingdom.

### Energy Contexts

Competing Technologies

<http://www.decc.gov.uk/>

The UK Department of Energy and Climate Change (DECC) website has a wide range of resources. The DECC energy modeller <http://2050-calculator-tool.decc.gov.uk> is a particularly useful source of ideas for scenarios – users can change various parameters on supply and demand to see what might happen over the period if different policy options were selected.

<http://www.energy.gov/>

The US Department of Energy also has a very comprehensive website, which offers an alternative perspective on some technology assessments.

### Climate

<http://www.ipcc.ch/>

The Intergovernmental Panel on Climate Change is generally regarded as the most authoritative source on the global implications of climate change. The reports used in this document are regularly reviewed and updated.

<http://www.defra.gov.uk/>

The UK Department for Environment, Farming and Rural Affairs (DEFRA) also has responsibilities for some aspects of climate change and public policy in the UK, complementing those of DECC.

### Environment

Apart from the DEFRA website above, useful information can be found at

<http://www.environment-agency.gov.uk/>

<http://www.naturalengland.org.uk/>

## Economy

If you are not confident with this area, the amount of data and critical analysis can be daunting. In this case, you may find it as easy to look at the financial pages of some of the major UK broadsheet newspapers like The Times, The Guardian, The Independent or the Daily Telegraph. These do a good job of explaining what is happening, although you should try to look at more than one because their analyses can be coloured by the newspaper's wider political allegiances. If you want to go to the original materials, UK public data and analyses can be found at

<http://www.hm-treasury.gov.uk/>

The Treasury website is the official voice of the incumbent UK government

<http://budgetresponsibility.independent.gov.uk/>

The Office of Budgetary Responsibility was set up in 2010 with the objective of providing an independent view on UK economic data, although it remains a public body.

<http://www.bankofengland.co.uk/>

The Bank of England has an independent responsibility for monetary policy and its reports often present a critical analysis of government economic management as a background to its own decisions.

It is often useful to complement these by looking at reports from international organizations, who tend to be more sceptical about UK economic performance in a comparative context. The most useful come from the International Monetary Fund <http://www.imf.org> and the Organization for Economic Co-operation and Development <http://www.oecd.org>

### Demography

<http://www.statistics.gov.uk>

The Office of National Statistics covers the whole of the UK, although some data are fed in from the devolved nations and analysed separately for those territories. The ONS produces regular and helpful reports on population trends for the UK as a whole.

### Location

<http://www.communities.gov.uk>

Land use planning in England is mainly overseen by the Department for Communities and Local Government, although most implementation rests with local government.

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If you are trying to customize scenarios for a particular area, you will probably find that there is useful material on city, county or district council websites (in England). Each of the devolved nations has its own framework and these should be examined separately.

### **Culture**

This is the most difficult to suggest resources for. The most useful come in the output from NGOs, particularly those operating in the environmental field, which challenge some of the values assumed by those who favour technological solutions that leave present lifestyles largely untouched. The Nuffield Council on Bioethics report on Biofuels exposes a lot of this debate, although it does not go very far into the position of those who would argue for a fundamental reorientation of society to a less mobile and technologically-intensive way of life. Mainstream Green thinking is well reflected on the Green Party website <http://www.greenparty.org.uk/> and the text above points to some other resources that are more fundamentalist – a Google search on ‘deep ecology’ will identify others. A useful source on pro-market thinking can be the Economist Intelligence Unit <http://www.eiu.com/public/> although there is a paywall around some of its most interesting material.

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## References

- Accenture. 2009. *Betting on Science: Disruptive Technologies in Transport Fuels*. London: Accenture.
- Air Transport Action Group. 2009. *Beginner's Guide to Aviation Biofuels*. Geneva.
- Alcamo, J, J.M. Moreno, B Novaky, M Bindi, R Corobov, R.J.N. Devoy, C Giannakopoulos, E Martin, J.E. Olesen, and A Shvidenko. 2007. Europe. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, 541-80. Cambridge, UK: Cambridge University Press.
- Alvarez, H. and Steinbüchel, A. (2002) Triacylglycerols in prokaryotic microorganisms. *Applied Microbiology and Biotechnology* 60(4): 367-376.
- Andrade, J.E., A. Pérez, P.J. Sebastian, and D. Eapen. 2011. "A review of bio-diesel production processes." *Biomass and Bioenergy* 35 (3) (March): 1008-1020. doi:10.1016/j.biombioe.2010.12.037.
- Antoni, D., Zverlov, V. and Schwarz, W. (2007) Biofuels from microbes. *Applied Microbiology and Biotechnology* 77(1): 23-35.
- Atsumi, S., Cann, A., Connor, M., Shen, C., Smith, K., Brynildsen, M., Chou, K., Hanai, T. and Liao, J. (2008) Metabolic engineering of *Escherichia coli* for 1-butanol production. *Metabolic Engineering* 10(6): 305-311.
- Balat, M. and Balat, H. (2009) Recent trends in global production and utilization of bio-ethanol fuel. *Applied Energy* 86(11): 2273-2282.
- Banister, David, Carey Newson, and Matthew Ledbury. 2007. *THE COSTS OF TRANSPORT ON THE ENVIRONMENT – THE ROLE OF TELEWORKING IN REDUCING CARBON EMISSIONS*. Transport Studies Unit. Oxford: Oxford University Centre for the Environment.
- Bank of England. 2010. *Monetary Policy Roundtable, 15 December 2009*. London: Bank of England. <http://www.bankofengland.co.uk/publications/other/monetary/roundtable/091215.pdf>.
- . 2011. *Monetary Policy Roundtable, 14 December 2010*. London: Bank of England. <http://www.bankofengland.co.uk/publications/other/monetary/roundtable/110120.pdf>.
- BBC. 2004. Kent's champagne popping prospect. *BBC News*. <http://news.bbc.co.uk/1/hi/england/3629187.stm>.
- Bolwell, G. P. (2000) Biosynthesis of plant cell wall polysaccharides. *Trends in Glycoscience and Glycotechnology* 12: 143-160.
- Bowles, Samuel. 1998. "Endogenous Preferences: The Cultural Consequences of Markets and Other Economic Institutions." *Journal of Economic Literature* 36 (1) (March 1): 75-111.
- Callen, Tim, and Jonathan David Ostry. 2003. *Japan's Lost Decade: Policies for Economic Revival*. Washington, DC: International Monetary Fund.
- de Cerqueira Leite, R. C. (2004) *Energy from Biomass*. Report for the IUPAP Working Group on Energy [http://pi.physik.uni-bonn.de/heinloth/www/III\\_5\\_Energy%20from%20Biomass.doc](http://pi.physik.uni-bonn.de/heinloth/www/III_5_Energy%20from%20Biomass.doc). Accessed February 2011.
- Chiaromonti, David, Andrea Maria Rizzo, Matteo Prussi, Silvana Tedeschi, Francesco Zimbardi, Giacobbe Braccio, Egidio Viola, and Paolo Taddei Pardelli. 2011. "2nd generation lignocellulosic bioethanol: is torrefaction a possible approach to biomass pretreatment?" *Biomass Conversion and Biorefinery* 1 (1) (February): 9-15. doi:10.1007/s13399-010-0001-z.
- Chisti, Y. (2007) Biodiesel from microalgae. *Biotechnology Advances* 25(3): 294-306.
- Clark, Peter. 1979. "Migration in England during the Late Seventeenth and Early Eighteenth Centuries." *Past & Present* (83) (May 1): 57-90.
- Commission of the European Communities. 2006. *An EU Strategy for Biofuels Impact Assessment*. Brussels: Commission of the European Communities.
- Committee on Climate Change. 2010. *Building a low-carbon economy – the UK's innovation challenge*. London.
- Committee on Water Implications of Biofuels Production in the United States. 2008. *WATER IMPLICATIONS OF BIOFUELS PRODUCTION IN THE UNITED STATES*. Washington, DC: THE NATIONAL ACADEMIES PRESS.
- CONCAWE Ad Hoc Group on Alternative Fuels. 2002. *energy and greenhouse gas balance of biofuels for europe - an update*. Brussels: CONCAWE.
- Consortium for Science, Policy and Outcomes. 2010. *FOUR POLICY PRINCIPLES FOR ENERGY INNOVATION & CLIMATE CHANGE: A SYNTHESIS*. Washington, DC: Arizona State University.
- CR, F., D, K.-M. and G, S. (2008) Selection and optimization of microbial hosts for biofuels production. *Metabolic Engineering*
- Das, Debabrata, and T. Nejat Veziroglu. 2001. "Hydrogen production by biological processes: a survey of literature." *International Journal of Hydrogen Energy* 26 (1) (January): 13-28. doi:10.1016/S0360-3199(00)00058-6.
- Deanda, K., Zhang, M., Eddy, C. and Picataggio, S. (1996) Development of an arabinose-fermenting *Zymomonas mobilis* strain by metabolic pathway engineering. *Applied and environmental microbiology* 62(12): 4465.

- 
- De Cian, Enrica, Elisa Lanzi, and Roberto Roson. 2007. *The Impact of Climate Change on Energy Demand: a Dynamic Panel Analysis*. CMCC Research Paper. Venice: Centro Euro-Mediterraneo per i Cambiamenti Climatici.
- DEFRA. 2007a. *UK Biomass Strategy*. London: DEFRA.
- . 2007b. *Planting and Growing Miscanthus: Best Practice Guidelines for Application to Defra's Energy Crops Scheme*. London: DEFRA.
- . 2010. *UK Climate Projections: Briefing report*. London: DEFRA.
- Dellomonaco, Clementina, Fabio Fava, and Ramon Gonzalez. 2010. "The path to next generation biofuels: successes and challenges in the era of synthetic biology." *Microbial Cell Factories* 9 (1): 3. doi:10.1186/1475-2859-9-3.
- Demirbas, A. (2009) *Biohydrogen: For Future Engine Fuel Demands* (ed). London, Springer
- Department of Communities and Local Government. 2010. *Household Projections, 2008 to 2033, England*. Housing Statistical Release. London: Department of Communities and Local Government.
- Department of Energy and Climate Change. 2010. *2050 Pathways Analysis*. London: Department of Energy and Climate Change.
- Dien, B., Cotta, M. and Jeffries, T. (2003) Bacteria engineered for fuel ethanol production: current status. *Applied Microbiology and Biotechnology* 63(3): 258-266.
- Drengson, Alan R., and Yuichi Inoue, eds. 1995. *The deep ecology movement: an introductory anthology*. Berkeley, CA: North Atlantic Books.
- E4Tech. 2009. *Biomass supply curves for the UK*. London.
- Economic Policy Committee and the European Commission (DG ECFIN). 2006. *The impact of ageing on public expenditure: projections for the EU25 Member States on pensions, health care, longterm care, education and unemployment transfers (2004-2050)*. European Economy Special Report. Brussels: EUROPEAN COMMISSION DIRECTORATE-GENERAL FOR ECONOMIC AND FINANCIAL AFFAIRS.
- Energy Research Partnership. 2010. *Energy Innovation Milestones to 2050*. London: Energy Research Partnership.
- Environment Agency. 2007. *Biofuels for transport position statement*. London: Environment Agency.
- European Environment Agency. 2006. *How much bioenergy can Europe produce without harming the environment?* Luxembourg: Office for Official Publications of the European Communities.
- Eriksson, M. E., Israelsson, M., Olsson, O. and Moritz, T. (2000) Increased gibberellin biosynthesis in transgenic trees promotes growth, biomass production and xylem fiber length. *Nature Biotechnology* 18: 784–788.
- Evans, R Keith. 2008. *Lithium Abundance - World Lithium Reserve*. R Keith Evans. <http://lithiumabundance.blogspot.com/>.
- Ezeji, T., Milne, C., Price, N. and Blaschek, H. (2010) Achievements and perspectives to overcome the poor solvent resistance in acetone and butanol-producing microorganisms. *Applied Microbiology and Biotechnology* 85(6): 1697-1712.
- Ezeji, T., Qureshi, N. and Blaschek, H. (2007) Butanol production from agricultural residues: Impact of degradation products on *Clostridium beijerinckii* growth and butanol fermentation. *Biotechnology and bioengineering* 97(6): 1460-1469.
- Farrell, A. E., Plevin, R. J., Turner, B. T., Jones, A. D., O'Hare, M. and Kammen, D. M. (2006) Ethanol Can Contribute to Energy and Environmental Goals. *Science* 311(5760): 506-508.
- Formanek, J., Mackie, R. and Blaschek, H. P. (1997) Enhanced butanol production by *Clostridium beijerinckii* BA101 grown in semidefined P2 medium containing 6 percent maltodextrin or glucose. *Applied and Environmental Microbiology* 63(6): 2306-2310.
- Fortman, J. L., Chhabra, S., Mukhopadhyay, A., Chou, H., Lee, T. S., Steen, E. and Keasling, J. D. (2008) Biofuel alternatives to ethanol: pumping the microbial well. *Trends in Biotechnology* 26(7): 375-381. Forum for the Future. 2008. *climate futures: responses to climate change in 2030*. London: Forum for the Future.
- de Fraiture, Charlotte, Mark Giordano, and Youngsong Liao. 2008. "Biofuels and implications for agricultural water use: blue impacts of green energy." *Water Policy* 10 (Supplement 1): 67-81.
- Frost, Martin. 2006. *The Structure of Commuting Flows in Rural England and Wales 1: An Initial Report*. London: Rural Evidence Research Centre.
- Fukuda, H., Kondo, A. and Noda, H. (2001) Biodiesel fuel production by transesterification of oils. *Journal of Bioscience and Bioengineering* 92(5): 405-416.
- Galor, Oded, and David N. Weil. 2000. "Population, Technology, and Growth: From Malthusian Stagnation to the Demographic Transition and beyond." *The American Economic Review* 90 (4): 806-828.
- Geels, Frank W., and Wim A. Smit. 2000. "Failed technology futures: pitfalls and lessons from a historical survey." *Futures* 32: 867-885.
-

- Godfray, H. Charles J., Ian R. Crute, Lawrence Haddad, David Lawrence, James F. Muir, Nicholas Nisbett, Jules Pretty, Sherman Robinson, Camilla Toulmin, and Rosalind Whiteley. 2010. "The future of the global food system." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365 (1554): 2769-2777. doi:10.1098/rstb.2010.0180.
- Gouda, M., Omar, S. and Aouad, L. (2008) Single cell oil production by *Gordonia* sp. DG using agro-industrial wastes. *World Journal of Microbiology and Biotechnology* 24(9): 1703-1711.
- Gray, K. A., Zhao, L. and Emptage, M. (2006) Bioethanol. *Current Opinion in Chemical Biology* 10(2): 141-146.
- Haber, Steffen. 2010. Chemetall: The lithium company. In Las Vegas.
- Hahn-Hägerdal, B., Karhumaa, K., Fonseca, C., Spencer-Martins, I. and Gorwa-Grauslund, M. (2007) Towards industrial pentose-fermenting yeast strains. *Applied Microbiology and Biotechnology* 74(5): 937-953.
- Hasegawa, F., Yokoyama, S. and Imou, K. (2010) Methanol or ethanol produced from woody biomass: Which is more advantageous? *Bioresource Technology* 101(1, Supplement 1): S109-S111.
- Heggenstaller, A. H., Anex, R. P., Liebman, M., Sundberg, D. N. and Gibson, L. R. (2008) Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agronomy* 100: 1740-1748.
- Higashide, Wendy, Yongchao Li, Yunfeng Yang, and James C. Liao. 2011. "METABOLIC ENGINEERING OF CLOSTRIDIUM CELLULOLYTICUM FOR ISOBUTANOL PRODUCTION FROM CELLULOSE." *Appl. Environ. Microbiol.* (March 4): AEM.02454-10. doi:10.1128/AEM.02454-10.
- Horton, C. E., Huang, K.-X., Bennett, G. N. and Rudolph, F. B. (2003) Heterologous expression of the *Saccharomyces cerevisiae* alcohol acetyltransferase genes in *Clostridium acetobutylicum* and *Escherichia coli* for the production of isoamyl acetate. *Journal of Industrial Microbiology & Biotechnology* 30(7): 427-432.
- Hull, A., Golubkov, I., Kronberg, B., Marandzheva, T. and Stam, J. (2006) An Alternative Fuel for Spark Ignition Engines. *International Journal of Engine Research* 7(3): 203-214.
- IFP. 2007. Potential biomass mobilization for biofuel production worldwide, in Europe and in France. Paris: IFP.
- Ingram, L. O., Aldrich, H., Borges, A., TB, C., Martinez, A., Morales, F., Saleh, A., Underwood, S., Yomano, L. and York, S. (1999) Enteric bacterial catalysts for fuel ethanol production. *Biotechnology Program* 15: 855-866.
- Ingram, L. O., Conway, T., Clark, D. P., Sewell, G. W. and Preston, J. F. (1987) Genetic engineering of ethanol production in *Escherichia coli*. *Appl. Environ. Microbiol.* 53(10): 2420-2425.
- Intergovernmental Panel on Climate Change. 2007. AR4 SYR Synthesis Report Summary for Policymakers - 3 Project climate change and its impacts. [http://www.ipcc.ch/publications\\_and\\_data/ar4/syr/en/spms3.html](http://www.ipcc.ch/publications_and_data/ar4/syr/en/spms3.html).
- International Partnership for Hydrogen and Fuel Cells in the Economy. 2010. 2010 Hydrogen and Fuel Cell Global Commercialization & Development Update. Berlin: International Partnership for Hydrogen and Fuel Cells in the Economy.
- Joachimsthal, E. and Rogers, P. (2000) Characterization of a high-productivity recombinant strain of *Zymomonas mobilis* for ethanol production from glucose/xylose mixtures. *Applied biochemistry and biotechnology* 84(1): 343-356.
- Kalscheuer, R., Stolting, T. and Steinbuchel, A. (2006) Microdiesel: *Escherichia coli* engineered for fuel production. *Microbiology* 152(9): 2529.
- Kemp, Martin, and Josie Wexler. 2010. ZERO CARBON BRITAIN 2030 A NEW ENERGY STRATEGY: The second report of the Zero Carbon Britain project. Llywngwern, Machynlleth, Powys: Centre for Alternative Technology.
- Knothe, G. (2005) Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. *Fuel Processing Technology* 86(10): 1059-1070.
- Köse, Ö., Tüter, M. and Aksoy, H. A. (2002) Immobilized *Candida antarctica* lipase-catalyzed alcoholysis of cotton seed oil in a solvent-free medium. *Bioresource Technology* 83(2): 125-129.
- Kuyper, M., Harhangi, H. R., Stave, A. K., Winkler, A. A., Jetten, M. S., de Laat, W. T., den Ridder, J. J., Op den Camp, H. J., van Dijken, J. P. and Pronk, J. T. (2003) High-level functional expression of a fungal xylose isomerase: the key to efficient ethanolic fermentation of xylose by *Saccharomyces cerevisiae*? *FEMS Yeast Research* 4(1): 69-78.
- Kuzuyama, T. (2002) Mevalonate and nonmevalonate pathways for the biosynthesis of isoprene units. *Bioscience, Biotechnology and Biochemistry* 66(8): 1619-1627.
- Lapuerta, M., Armas, O. and García-Contreras, R. (2008) Stability of diesel-bioethanol blends for use in diesel engines. *Fuel* 86(10-11): 1351-1357.
- Leahy, Terry. 2008. "Discussion of 'Global Warming and Sociology'." *Current Sociology* 56 (3): 475-484. doi:10.1177/0011392107088240.

- Lee, S., Chou, H., Ham, T., Lee, T. and Keasling, J. (2008) Metabolic engineering of microorganisms for biofuels production: from bugs to synthetic biology to fuels. *Current opinion in biotechnology* 19(6): 556-563.
- Li, Q., Du, W. and Liu, D. (2008) Perspectives of microbial oils for biodiesel production. *Applied Microbiology and Biotechnology* 80(5): 749-756.
- Li, Zhimin, Yan Liu, Wei Liao, Shulin Chen, and Robert S. Zemetra. 2011. "Bioethanol production using genetically modified and mutant wheat and barley straws." *Biomass and Bioenergy* 35 (1) (January): 542-548. doi:10.1016/j.biombioe.2010.10.006.
- Liu, B. and Zhao, Z. (2007) Biodiesel production by direct methanolysis of oleaginous microbial biomass. *Journal of Chemical Technology & Biotechnology* 82(8): 775-780.
- LO, I., T, C., DP, C., GW, S. and JF, P. (1987) Genetic engineering of ethanol production in *Escherichia coli*. *Applied Environmental Microbiology* 53: 2420–2425.
- Lux Research. 2009. *Unplugging the Hype around Electric Vehicles*. Boston: Lux Research.
- . 2010. *Bio-based Fuels and Materials through 2015: Growing Capacity Past a Drop in the Bucket*. Boston: Lux Research.
- Lynd, L. (1996) Overview and evaluation of fuel ethanol from cellulosic biomass: technology, economics, the environment, and policy. *Annual review of energy and the environment* 21(1): 403-465.
- Marland, G., and A.F. Turhollow. 1991. "CO<sub>2</sub> emissions from the production and combustion of fuel ethanol from corn." *Energy* 16 (11-12): 1307-1316. doi:10.1016/0360-5442(91)90004-6.
- Martin, V. J. J., Pitera, D. J., Withers, S. T., Newman, J. D. and Keasling, J. D. (2003) Engineering a mevalonate pathway in *Escherichia coli* for production of terpenoids. *Nat Biotech* 21(7): 796-802.
- Meridian International Research. 2008. *The Trouble with Lithium 2: Under the Microscope*. Martainville, France: Meridian International Research.
- Metzger, P. and Largeau, C. (2005) *Botryococcus braunii*: a rich source for hydrocarbons and related ether lipids. *Applied Microbiology and Biotechnology* 66(5): 486-496.
- Mielenz, J. (2001) Ethanol production from biomass: technology and commercialization status. *Current Opinion in microbiology* 4(3): 324-329.
- Mitchell, James, and Nigel Pain. 2003. *The Determinants of International Migration into the UK: A Panel Based Modelling Approach*. London: National Institute of Economic and Social Research.
- Mukhopadhyay, A., Redding, A., Rutherford, B. and Keasling, J. (2008) Importance of systems biology in engineering microbes for biofuel production. *Current opinion in biotechnology* 19: 228-234.
- Niven, R. (2005) Ethanol in gasoline: environmental impacts and sustainability review article. *Renewable and Sustainable Energy Reviews* 9(6): 535-555.
- Nuffield Council on Bioethics. 2011. *Biofuels: Ethical Issues*. London: Nuffield Council on Bioethics.
- Odeh, Inakwu O. A., Daniel K. Y. Tan, and Tihomir Ancev. 2011. "Potential Suitability and Viability of Selected Biodiesel Crops in Australian Marginal Agricultural Lands Under Current and Future Climates." *BioEnergy Research* (January). doi:10.1007/s12155-010-9110-6. <http://www.springerlink.com/content/p0700v6380722575/>.
- Office of Budgetary Responsibility. 2011. *Fiscal sustainability report*. London: Office of Budgetary Responsibility.
- Office of National Statistics. 2009. *National population projections, 2008-based*. *Statistical Bulletin*. London: Office of National Statistics. <http://www.statistics.gov.uk/pdfdir/pproj1009.pdf>.
- . 2010. *Live births in England and Wales by characteristics of mother 2009*. *Statistical Bulletin*. London: Office of National Statistics. <http://www.statistics.gov.uk/pdfdir/birth1010.pdf>.
- Optimum Population Trust. OPT — Towards Sustainable and Optimum Populations. <http://www.optimumpopulation.org/opt.optimum.html>.
- Ouyang, J., Kong, F., Su, G., Hu, Y. and Song, Q. (2009) Catalytic Conversion of Bio-ethanol to Ethylene over La-Modified HZSM-5 Catalysts in a Bioreactor. *Catalysis Letters* 132(1): 64-74.
- Patnayak, S. and Sree, A. (2005) Screening of bacterial associates of marine sponges for single cell oil and PUFA. *Letters in applied microbiology* 40(5): 358-363.
- Persson, S., Wei, H., Milne, J., Page, G. P. and Somerville, C. R. (2005) Identification of genes required for cellulose synthesis by regression analysis of public microarray data sets. *Proceedings of the National Academy of Sciences USA* 102: 8633–8638.
- Pinto, A., Guarieiro, L., Rezende, M., Ribeiro, N., Torres, E., Lopes, W., Pereira, P. and Andrade, J. (2005) Biodiesel: an overview. *Journal of the Brazilian Chemical Society* 16: 1313-1330.
- Pitera, D. J., Paddon, C. J., Newman, J. D. and Keasling, J. D. (2007) Balancing a heterologous mevalonate pathway for improved isoprenoid production in *Escherichia coli*. *Metabolic Engineering* 9(2): 193-207.

- 
- Posen, Adam. 2010. THE REALITIES AND RELEVANCE OF JAPAN'S GREAT RECESSION: NEITHER RAN NOR RASHOMON presented at the STICERD Public Lecture, May 24, London School of Economics. <http://www.bankofengland.co.uk/publications/speeches/2010/speech434.pdf>.
- Prince, R. C. and Kleshgi, H. S. (2005) The photobiological production of hydrogen: potential efficiency and effectiveness as a renewable fuel. *Critical Reviews in Microbiology* 31(1): 19-31.
- Qureshi, N., Saha, B. C., Dien, B., Hector, R. E. and Cotta, M. A. (2010) Production of butanol (a biofuel) from agricultural residues. I. Use of barley straw hydrolysate. *Biomass and Bioenergy* 34: 559-565.
- Ragauskas, A., Williams, C., Davison, B., Britovsek, G., Cairney, J., Eckert, C., Frederick Jr, W., Hallett, J., Leak, D. and Liotta, C. (2006) The path forward for biofuels and biomaterials. *Science* 311(5760): 484.
- Ragauskas, A. J., Williams, C. K., Davison, B. H., Britovsek, G., Cairney, J., Eckert, C. A., Jr, W. J. F., Hallett, J. P., Leak, D. J., Liotta, C. L., Mielenz, J. R., Murphy, R., Templer, R. and Tschaplinski, T. (2006) The Path Forward for Biofuels and Biomaterials *Science* 311: 484-489
- Razi, Zvi. 1993. "The Myth of the Immutable English Family." *Past & Present* (140): 3-44.
- Reilly, Michael, and Dirk Willenbockel. 2010. "Managing uncertainty: a review of food system scenario analysis and modelling." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365 (1554): 3049 -3063. doi:10.1098/rstb.2010.0141.
- Ribeiro, N., Pinto, A., Quintella, C., da Rocha, G., Teixeira, L., Guarieiro, L., do Carmo Rangel, M., Veloso, M., Rezende, M. and da Cruz, R. (2007) The role of additives for diesel and diesel blended (ethanol or biodiesel) fuels: a review. *Energy Fuels* 21(4): 2433-2445.
- Righelato, Renton, and Dominick V. Spracklen. 2007. "Carbon Mitigation by Biofuels or by Saving and Restoring Forests?" *Science* 317 (17 August): 902.
- Ro, D.-K., Paradise, E. M., Ouellet, M., Fisher, K. J., Newman, K. L., Ndungu, J. M., Ho, K. A., Eachus, R. A., Ham, T. S., Kirby, J., Chang, M. C. Y., Withers, S. T., Shiba, Y., Sarpong, R. and Keasling, J. D. (2006) Production of the antimalarial drug precursor artemisinic acid in engineered yeast. *Nature* 440(7086): 940-943.
- Rosillo-Calle, F. and Cortez, L. (1998) Towards ProAlcool II--a review of the Brazilian bioethanol programme. *Biomass and Bioenergy* 14(2): 115-124.
- Rubin, E. M. (2008) Genomics of Cellulosic Biofuels. *Nature* 454: 841-846.
- Ryan, Catie. 2009. *Cultivating Clean Energy: The Promise of Algae Biofuels*. New York: Natural Resources Defense Council.
- Schwarz, W. and Gapes, J. (2006) Butanol—rediscovering a renewable fuel. *BioWorld Europe* 1: 16-19.
- Shah, S., Sharma, S. and Gupta, M. N. (2004) Biodiesel Preparation by Lipase-Catalyzed Transesterification of Jatropha Oil. *Energy & Fuels* 18(1): 154-159.
- Shiba, Y., Paradise, E. M., Kirby, J., Ro, D.-K. and Keasling, J. D. (2007) Engineering of the pyruvate dehydrogenase bypass in *Saccharomyces cerevisiae* for high-level production of isoprenoids. *Metabolic Engineering* 9(2): 160-168.
- Solomon, B. and Luzadis, V. (2009) *Renewable Energy from Forest Resources in the United States* (ed). New York, Routledge
- Stephanopoulos, G. (2007) Challenges in Engineering Microbes for Biofuels *Production Science* 315: 801-804.
- Sticklen, M. (2006) Plant genetic engineering to improve biomass characteristics for biofuels. *Current opinion in biotechnology* 17(3): 315-319.
- Sticklen, M. (2008) Plant genetic engineering for biofuel production: towards affordable cellulosic ethanol. *Nature Reviews Genetics* 9(6): 433-443.
- Tahil, William. 2006. *The Trouble with Lithium: Implications of Future PHEV Production for Lithium Demand*. Martainville, France: Meridian International Research.
- Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C. and Williams, R. (2009) Beneficial Biofuels - the Food, Energy and Environment Trilemma *Science* 325: 270-271.
- Tsukahara, K. and Sawayama, S. (2005) Liquid Fuel Production Using Microalgae. *Journal of the Japan Petroleum Institute* 48(5): 251-259.
- Tummala, S., Junne, S. and Papoutsakis, E. (2003) Antisense RNA downregulation of coenzyme A transferase combined with alcohol-aldehyde dehydrogenase overexpression leads to predominantly alcohologenic *Clostridium acetobutylicum* fermentations. *Journal of bacteriology* 185(12): 3644.
- Tummala, S., Welker, N. and Papoutsakis, E. (2003) Design of antisense RNA constructs for downregulation of the acetone formation pathway of *Clostridium acetobutylicum*. *Journal of bacteriology* 185(6): 1923.
- Tyson, K., Bozell, J., Wallace, R., Petersen, E., Moens, L. and CO, N. R. E. L. G. (2004) Biomass oil analysis: research needs and recommendations.
-

- 
- URS Corporation. 2010. Adapting Energy, Transport and Water Infrastructure to the Long-term Impacts of Climate Change. London.
- Volk, T. A., Verwijst, T., Tharakan, P. J., Abrahamson, L. P. and White, E. H. (2004) Growing fuel: a sustainability assessment of willow biomass crops. *Frontiers in Ecology and the Environment* 2(8): 411-418.
- Wackett, L. (2008) Biomass to fuels via microbial transformations. *Current Opinion in Chemical Biology* 12(2): 187-193.
- Wake, L. V. and Hillen, L. W. (1980) Study of a "bloom" of the oil-rich alga *Botryococcus braunii* in the Darwin River Reservoir. *Biotechnology and bioengineering* 22(8): 1637-1656.
- Weil, J., Westgate, P., Kohlmann, K. and Ladisch, M. (1994) Cellulose pretreatments of lignocellulosic substrates. *Enzyme and microbial technology* 16(11): 1002-1004.
- Wentzel, A., Ellingsen, T., Kotlar, H., Zotchev, S. and Throne-Holst, M. (2007) Bacterial metabolism of long-chain n-alkanes. *Applied Microbiology and Biotechnology* 76(6): 1209-1221
- Wilhelm, W. W., Johnson, J. M. F., Karlen, D. L. and Lightle, D. T. (2007) Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy* 99: 1665.
- Williams, Katie. 2009. "Space per person in the UK: A review of densities, trends, experiences and optimum levels." *Land Use Policy* 26 (Supplement 1) (December): S83-S92. doi:10.1016/j.landusepol.2009.08.024.
- Withers, S. T., Gottlieb, S. S., Lieu, B., Newman, J. D. and Keasling, J. D. (2007) Identification of Isopentenol Biosynthetic Genes from *Bacillus subtilis* by a Screening Method Based on Isoprenoid Precursor Toxicity. *Appl. Environ. Microbiol.* 73(19): 6277-6283.
- Xiao-Ling, M. and Qing-Yu, W. (2004) Bio-oil fuel production from microalgae after heterotrophic growth. *Renewable Energy*: 04.
- Xu, H., Miao, X. and Wu, Q. (2006) High quality biodiesel production from a microalga *Chlorella protothecoides* by heterotrophic growth in fermenters. *Journal of Biotechnology* 126(4): 499-507.
- Yadvika, S., Sreerishnan, T., Kohli, S. and Rana, V. (2004) Enhancement of biogas production from solid substrates using different techniques-a review. *Bioresource Technology* 95(1): 1-10.
- Yoon, S. H., Park, H. M., Kim, J. E., Lee, S. H., Choi, M. S., Kim, J. Y., Oh, D. K., Keasling, J. D. and Kim, S. W. (2007) Increased -Carotene Production in Recombinant *Escherichia coli* Harboring an Engineered Isoprenoid Precursor Pathway with Mevalonate Addition. *Biotechnology Progress* 23(3): 599-605
- Zah, Rainer, Claudia Binder, Stefan Bringezu, Jurgen Reinhard, Alfons Schmid, and Helmut Schutz. 2010. Future Perspectives of 2nd Generation Biofuels. Zurich: Centre for Technology Assessment, ETH.
- Zhang, M., Eddy, C., Deanda, K., Finkstein, M. and Picataggio, S. (1995) Metabolic engineering of a pentose metabolism pathway in ethanologenic *Zymomonas mobilis*. *Science* 267(240-243).
- Zheng, Y. N., Li, L. Z., Xian, M., Ma, Y. J., Yang, J. M., Xu, X. and He, D. Z. (2009) Problems with the microbial production of butanol. *Journal of Industrial Microbiology and Biotechnology* 36(9): 1127-1138.
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