Learning from tough plants about photosynthesis

Plants growing in some of the most arid regions on earth have had to develop different photosynthesis systems to cope with water shortages and heat. Their mechanisms help us gain valuable insights for future bioenergy and food crops.

How do some plants manage to survive in the most arid regions on earth? Professor Andrew Smith from Plant Sciences at Oxford is exploring this question, and has identified genetic differences and photosynthesis mechanisms that could be beneficial for bioenergy and food crops more widely.

Plants like pineapples and agaves have adapted their photosynthesis process in a remarkable way. Unlike other plants, which open the stomata in their leaves during the day to take in CO₂, these plants minimise water loss by only capturing CO₂ at night instead. This form of photosynthesis, known as crassulacean acid metabolism (CAM), stores malic acid in the cells overnight and breaks it down to release CO₂ using sunlight during the day. The leaves of such plants are rich in simple sugars, which help protect the plant in extreme conditions and assist with water retention. These sugars provide the energy store and are ideal for conversion to fuels, such as bioethanol.

The change of high quality farm land from food to fuel production and the destruction of natural habitats has raised concerns over the sustainability of bioenergy crop production, with e.g. 40% of the U.S. maize crop currently used to make ethanol. This drawback does not apply to CAM plants.

CAM plants can be grown on land that is unsuitable for most other purposes. Worldwide, there are tens of millions of hectares of degraded land. Better still, some of these regions could be re-cultivated by growing CAM plants. For instance, 95% of the Madagascan original vegetation has been lost. CAM plants could provide a route towards regenerating regions that might otherwise deteriorate further, as well as providing a source of income and energy for local people.

Oxford researchers from Plant Sciences and Engineering are now exploring ways to grow such crops commercially. One idea is to use sisal, a species of agave traditionally grown for fibre in African countries. It needs no irrigation or fertiliser, and the plants can live for 25 years. At present the long fibres are stripped out of the sisal leaves and the remaining soft tissue (65% of leaf biomass) is literally ‘washed down the drain’. The pulp could instead be fermented to produce fuels. Pineapple leaves—also currently discarded—could be used in the same way.

Questions remain over the scalability of this industry, as the harvest is a labour intensive process and difficult to automate. Current bioethanol fermentation plants are large scale operations, requiring around 20,000 tonnes of feedstock per day. Oxford research is seeking to develop small scale digester plants to support local production and reduce transportation cost and impact, which could make CAM plants a valuable source of energy in many developing countries with presently insufficient access to energy.
Nanoparticle catalysts for methanol and hydrogen production

Professor Edman Tsang and his group develop new catalysts using nano-particles to convert biomass to methanol for transport applications, and to produce high-purity hydrogen for use in fuel cells for portable devices.

Methanol produced from biomass is widely considered an attractive option in terms of reducing our reliance on fossil fuels for transport. The chemical industry already uses methanol extensively and biomass is a globally available and inexpensive resource. Professor Edman Tsang in the Chemistry Department at Oxford is developing better processes to convert biomass to methanol.

Such processes already exist, but they require a high-energy step to completely break down the biomass before reassembly into methanol, making the conversion inefficient and expensive. More efficient production methods are needed if bio-methanol is to become a fuel of the future.

The toxicity of methanol precludes the use of enzymes. Professor Tsang and his group are therefore focusing on new catalytic methods. They developed the first catalyst capable of driving the synthesis of methanol from biomass. This catalyst, based on carefully-tailored metallic nanoparticles, is capable of producing high yields of methanol at low temperatures and pressures, greatly reducing the operational cost of the reaction.

Methanol is also of interest as a source of hydrogen for energy generation in fuel cells. Hydrogen is an excellent low-carbon fuel, but its low energy-to-volume ratio and hazardous storage make it impractical for use in small-scale devices. Storage in the form of liquid methanol followed by release on demand is a favourable alternative.

Chemical reactions used so far to liberate hydrogen are complex, require high temperatures, and generate carbon monoxide impurities which damage fuel cells. These drawbacks have limited the use of methanol as a hydrogen storage fuel.

Professor Tsang’s group has developed a new catalyst, among the first of its kind, which can produce high-purity hydrogen in a single, low-temperature step. This catalyst, also based on metallic nanoparticles, opens up the possibility of using small-scale cells with rechargeable liquid fuel cartridges to power portable devices.

These new technologies are now in the process of being commercialised through ISIS Innovations, Oxford’s technology transfer company, in order to realise their full potential to provide a new, sustainable, and low-carbon energy source.

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The exponential growth in solar photovoltaics (PV) over recent years has surpassed the expectations of many. However, in absolute terms its contribution to world energy is still small and the technology comparatively expensive. The most dramatic developments may therefore still lie ahead, if costs can be reduced further.

Now researchers at Oxford have developed a new class of photovoltaic cells that could do just that and may even surpass some of the most efficient products on the market.

The new material is an organo-metallic crystalline semiconductor material called perovskite and is in fact not that new at all. Back in the 1990s perovskites received considerable attention as a transistor and LED material. Curiously, they were overlooked for PV applications in favour of organic and thin-film PV, and only re-discovered as late as 2009.

Since then perovskites have taken the community by storm. First they were just used as an absorber material, but Professor Snaith and his team discovered that perovskites can do much more, and created a new highly successful solar cell based on perovskites.

Efficiencies are rapidly improving and already rival the best thin film PV materials. The fundamental properties are promising. Professor Snaith has set his ambitions on surpassing silicon—the dominant PV material—which would move perovskite cells from special applications, like building integrated PV, towards a mass market with substantial growth potential.

This ambition is supported by some of the key properties of this material, such as its high open circuit voltage, diffusion lengths and very low exciton binding energies. Once impurities and deposition processes have improved, efficiencies above 20% are expected to be possible based on these properties. The race is on to capitalise on this potential and start manufacturing modules.

And here lies another attraction of perovskites. They can be manufactured with conventional processes or with solution based methods, which would require neither vacuum nor high temperatures. Material and production cost of these cells could therefore be lower than conventional cells and their components could be less toxic and more abundant as well.

The importance of this work has not gone unnoticed. Nature magazine declared Henry Snaith to be one of the ten most important people of 2013, worldwide in all science. His work could have far reaching consequences for the use of PV as a low cost renewable source of future energy.

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Policy design to promote energy efficiency

The University of Oxford supports evidence based policy development and also identifies when and why policies may not deliver their desired effect. Policy research combines Oxford’s technical, business and social science backgrounds.

Energy policy is a diverse and complex field, with concerns cutting across multiple fields of traditional academic study. How can our energy system be made more efficient? How can we reduce the environmental impact of our energy use? How can we ensure that our energy supplies are secure and affordable? Policy interventions aim to aid our energy system by achieving answers to these questions and more. Critically evaluating the effectiveness of energy policies is essential if we are to achieve the large-scale transformations of global energy infrastructure that is required in the 21st century.

When considering energy systems, the focus is often directed largely at the supply side of the system. Whilst the methods and means of generating and supplying energy are of obvious importance, policies influencing energy demand also have a crucial role to play in creating a sustainable energy system.

The research of Dr Nick Eyre’s Lower Carbon Futures research group, based in Oxford University’s Environmental Change Institute (ECI), aims to assess the impacts of energy efficiency policies and propose new and innovative energy-demand policy concepts. The wide range of academic backgrounds within the Lower Carbon Futures group allows a broad-picture approach to be taken in the analysis of energy demand policy. The research pulls together and addresses the interactions between different policy elements on both the microeconomic and macroeconomic levels.

Analysing the impacts of existing governmental energy efficiency proposals needs to involve assessment of the regulation, standards and customer advice programmes. Recently, the group examined in detail the proposals of the Department of Energy and Climate Change (DECC) on energy efficiency in UK homes, known as the Green Deal. Using figures from DECC’s own impact assessment, the research showed, prior to its launch, that the Green Deal would be less effective than the policies that it is replacing. Academia has a key role to play in highlighting these kind of issues in order to facilitate an effective public discourse on the UK’s energy future.

The Group’s work on home insulation policies has demonstrated the scale of the policy challenge in getting householders to adopt technologies, and the importance of considering social factors in policies that hope to achieve a change in the real world. Policies such as the Green Deal need to achieve sufficient uptake on a nationwide scale to have the desired impact on energy use, and this requires an understanding of how to incentivise such schemes.

In an area as complex and broad as energy policy, there can be no silver bullet for all of the world’s energy challenges. The policy analysis and creation within the Lower Carbon Futures research group is crucial to understanding the options available. This insight will contribute to sensible and informed decisions being taken by governments to safeguard the world’s energy future.

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A low-cost solar cooker for the developing world

4 million people die each year from respiratory diseases caused by smoke inhalation from fuel used for cooking. Solar cookers are an innovative solution to this problem, which could enhance the quality of the lives of women and children.

A new solar cooker has been developed at the University of Oxford, demonstrating how fundamental research can lead to very practical applications. Originally, Professor Nick Jelley was working on maximising the light collected from solar neutrino interactions in the Sudbury Neutrino Observatory (SNO). For this he used Winston cones, parabolically shaped devices with a reflective inner surface. These concentrators had to survive many years under water. An exhaustive search for a suitably hard wearing and affordable material eventually led to a design with 18 curved reflective strips.

Now, Professor Jelley and his colleagues in the Department of Engineering have discovered that the same design principle could lead to lower cost, durable and more effective solar cookers. The Winston cone as a secondary concentrator could result in higher temperatures.

The new design has been adopted by Dytecna Ltd. and prototype cookers are now being built for field trials in Kenya.

No other solar cooker system so far developed can concentrate so much naturally available renewable energy into such a compact and usable solution.

Research funded by the Leverhulme Trust showed how two single curvature surfaces can focus sunlight in a suitable way for a solar cookers. The combination of a conical and a parabolic mirror directs the sun’s energy to the underside of a cooking platform. The single curvature surfaces in the concentrator allow the reflective surfaces to be formed from hardwearing flat reflective sheets. This approach reduces costs and enables the concentrator to be flat-packed—an essential requirement for disaster relief operations. The design is robust and easy to assemble.

With direct sunlight the cooker is designed to provide heating in excess of 200°C and can be used with a saucepan on a cooking surface, with an oven, or just with a suspended pot, at a standard worktop height. It is comfortable to use, particularly for the elderly or infirm, and much more hygienic than a cooker placed directly on the ground.

To track the sun, the mirror system merely has to be rotated about a ‘horizontal’ axis during the day; the axis is altered weekly to follow the seasonal variation in the sun’s path.

With simple additions it may also be used to dry food or as a water sterilisation system, enabling the use of scarce or contaminated water resources and helping in the prevention of sickness and disease.

The forthcoming Kenya trials (funded by an STFC mini-ips) and their evaluation will open up other exciting areas of research: thermal stores using phase change materials, which will not only enable evening cooking but may also use thermoelectric generators to provide electricity for lighting and mobiles (both web and phone).

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Modelling energy use in transport

Models developed at the University of Oxford help policy makers and many others to understand the environmental, social and economic implications of modern transport systems and to evaluate their impact in future scenarios.

An understanding of transport and mobility is widely regarded as a key component of policy making in a number of fields, from climate change mitigation to healthcare, and is of great interest to groups as diverse as governments, health professionals and charitable organisations. Forecasts of the changing effects of transport are therefore vital for effective decision-making, yet reliable predictions are difficult to obtain due to the magnitude and complexity of modern transport and mobility.

As part of the Environmental Change Institute, Dr. Christian Brand’s research is focussed around developing a greater understanding of the environmental, social and economic effects of transport and mobility on scales ranging from the individual to the national level. In particular, his work is concentrated on the goals of ensuring energy security and delivering a low carbon future for the UK.

His research into modelling future transport trends has led to the creation of the UK Transport Carbon Model (UKTCM), which allows potential energy or low carbon policies and ‘policy packages’ to be analysed over the long term according to different scenarios of socio-economic and demographic developments. The UKTCM has been hugely influential in describing and predicting the impact of future developments in transport energy usage and low carbon technology uptake on efforts to combat climate change; it has been used to estimate the likely increase in transport energy use and carbon emissions of the proposed increase to an 80mph speed limit on motorways and dual carriageways. Since its publication in February 2010, the UKTCM has been downloaded nearly 6,000 times and now leads the field in modelling the environmental effects of transport and mobility systems.

Dr. Brand’s work also encompasses the accurate measurement, monitoring and analysis of energy use behaviour at the local and household levels. Working alongside charitable organisations, he has been examining the effects of new walking and cycling schemes on travel behaviour and associated physical activity and carbon emissions impacts. This work, performed in collaboration with government departments and NGOs, has provided valuable evidence to inform policy at national and international levels.

The contribution of Oxford to this field has been highly influential; the design of accurate monitoring and modelling tools and techniques has assisted policymaking at the highest levels, and the focus on the wider environmental and social impacts of transport policy continues to affect approaches to a low-carbon future.

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Rethinking urban mobility

Professor David Banister and colleagues are rethinking urban transport solutions for the 21st century. To become more sustainable, it is essential to address our dependence on the car, and design transport solutions that can be integrated into our cities’ infrastructures.

In the last hundred years the increasing opportunity for ordinary people to travel has allowed us to expand our horizons both physically and mentally, and has changed our social structures and work-patterns beyond recognition. The car, the symbol of individual freedom in the developed world, has been integral to this revolution.

Despite its success, the petrol-driven car is taking an environmental toll on the world. Transport is responsible for 25% of global CO₂ emissions today. As large nations such as India and China continue to mature in their economic development, the demand for cars is expected to grow significantly, putting ever-increasing pressure on the environment. In the UK, the government has made a commitment to drastic cuts in greenhouse gas emissions by 2050, adding an even greater urgency to the debate on urban structure and travel. In addition to the environmental considerations, there are just too many cars on the road: traffic congestion is a serious problem in many cities.

The future of urban transport is one of the key issues addressed by Oxford’s Transport Studies Unit (TSU), an interdisciplinary research centre which specialises in the study of ‘transport futures’.

In coming up with a sustainable solution for urban transport in the 21st century, it is important to recognise that patterns of behaviour related to transport can be extremely resistant to change. Researchers at the TSU have drawn on ideas used in behavioural economics and transition theory to understand and model this inertia. The research shows that if you give travellers all the information they need to make a truly informed decision, it can enable them to move away from their currently car-centric modes of urban transport to the most efficient and environmentally sustainable combination of modes for a particular journey.

Another important area of TSU research concerns the subsidisation of new forms of transport that will help the transition from a car-dependent society. Subsidies can facilitate change; for example, the development of small speed-restricted electric vehicles offers the potential for a more efficient mode of urban transport if incentivised properly. However, the challenge for governments is how to ensure that any new technology moves from being subsidised to being independent of government financial support, and this requires detailed research.

Moving away from our dependence on the car is an important facet of rethinking urban mobility, but it is not the only consideration. TSU research is increasingly showing that urban structure and mobility are inextricably linked; there are significant associations between the built environment and travel. TSU policy papers highlight the need to design cities efficiently in order to maximise the capacity for low and zero-carbon journeys. Increasing urban densities and reducing urban sprawls can help facilitate transport patterns based on shorter journeys (less than 5km), which are suitable for cycling and walking.

Transport has a major impact on all aspects of our lives. Working towards an efficient and sustainable model of urban mobility will bring benefits for everyone who lives and works in a city.

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Understanding metal cracking in nuclear reactors

Professor Sergio Lozano-Perez’s research on Stress Corrosion Cracking, one of the most important issues affecting nuclear power plants, is making a major contribution to the safety of pressurised water reactors.

Nuclear power is likely to remain a key component of electricity generation in the developed world, especially as governments try to adopt low-carbon alternatives. The UK government, for example, has just given the go-ahead for the UK’s first new nuclear station in a generation at Hinkley Point C. It is vital that the most robust materials available are used in construction, since materials failure is not only dangerous but expensive.

In this context, the work of Professor Sergio Lozano-Perez is critically important. For the past ten years his group has studied Stress Corrosion Cracking (SCC) in the stainless steel and nickel alloys used in the construction of pressurised water reactors (PWRs). Under normal conditions these materials are extremely durable and corrosion-resistant. However, when subjected to the stressed conditions of a PWR, the alloys start to oxidise. Microscopic cracks develop in the metal along the grain boundaries (the planes where two crystals of metal meet), leading to the risk of unexpected and devastating failure. The cracks can take years to develop and are so difficult to detect, monitor and predict that for a long time the specific mechanisms that led to cracking remained a matter of speculation.

Now Professor Lozano-Perez’s research has led to a vastly improved understanding of SCC, through carefully-designed experiments that analyse the cracking mechanisms one factor at a time. Under simulated PWR conditions, Lozano-Perez and his collaborators create samples of alloy with the right SCC features; this in itself can take months. They then isolate and examine a minute part of the crack tip (an area just a few nanometres wide). Central to the experiments is the use of novel analytical techniques that enable a 3D-study of the materials at the atomic level. New discoveries include the following:

- Lithium is present in the oxide layers. Lithium and boron are added to PWR cooling water in tiny quantities to absorb excess neutrons from the fission reaction and control the pH. The discovery that Lithium (but not Boron) migrates from the water into the oxide layers shows that it may play a part in the oxidation process. Prior to these experiments the possible role of Lithium and Boron in SCC was purely a matter of speculation.
- Isolated ‘islands’ of oxide occur within supposedly intact metal, suggesting that atoms of oxygen pass through the metal and oxidise within it. ‘Internal oxidation’ was previously thought to be unlikely.
- Micro-cantilever tests have established exactly how the oxide in the cracks breaks, and how much stress it can take before it fractures. Previously the mechanics of oxide fracturing were unknown.

This pioneering and detailed approach has led to a vastly improved understanding of SCC in which a number of mechanisms can be seen to be acting together to cause cracking. As well as analysing the flaws in existing alloys and thus improving the ability to predict SCC, Lozano-Perez is also able to create new alloys that are more resistant to SCC, and this may have a major impact on future construction of nuclear power stations.

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Smart-phones become smart-meters

If you can’t measure it, you can’t improve it. This is the basis on which Oxford Spin-out Pilio helps businesses reduce their energy bills. Their innovative ideas ease the cost and effort involved in measuring and understanding energy use.

Reducing energy consumption is important for both businesses and households which seek to reduce their bills. A key problem is knowing where to start: where is energy being wasted? What energy-saving measures can and should be implemented?

In a bid to address these questions, Dr Russell Layberry at the Environmental Change Institute develops new solutions to help individuals and businesses to monitor and understand their energy use. Through Oxford spin-out company Pilio, his work has led to a number of software tools and monitoring solutions.

The focus is on making the process simple for users. Clients can input their own gas and electricity meter readings. The software automatically calibrates energy use with local weather data. These indicators can be compared with buildings of a similar size to give a sense of one’s performance. It takes about five minutes per week to input the energy readings. No extra meters or devices are required, and companies do not need to spend time designing their own spreadsheets to analyse data. Several hundred small and medium-sized businesses currently use the software.

Dr Layberry is now investigating the potential of smart-phones to monitor energy usage in real time, both at building and appliance level. Instead of expensive real-time monitoring systems, he uses Android phones, which are mass manufactured and offer a wealth of sensing and communication functionally at a fraction of the cost. The microphone socket, for example, can be used as a sensitive volt-meter. Combined with the right low cost ancillaries it can measure temperature, gas or electricity consumption. Even if no electrical signal is easily accessible, the phone’s accelerometer can tell whether a boiler pump is running, and image recognition software helps to ‘read’ meters and transmit the information.

And smart phones come with in-built communication. Once data has been collected it can be transferred using mobile or wi-fi networks. Their portability further helps in gathering data from as many locations as possible and building up a detailed picture over time without the need for multiple sensors.

With this information to hand it becomes easier to identify waste and engage people in reducing consumption. Pilio’s clients include the Royal Albert Hall, several theatres and even churches. With the additional information users are able to reduce consumption by between 10% and 40%.

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At present some 80% of our energy is derived from the combustion of chemical fuels, whether for transport, heating or power generation. While this is an inexpensive way of meeting our energy needs, the burning of fossil fuels by current methods leads to the production of harmful soot particles, noxious compounds such as nitrogen oxides, and greenhouse gases.

Understanding the complex chemistry of combustion is important for improving the efficiency of the reaction, leading to increased energy output with decreased emissions of harmful by-products. Owing to the global extent of combustion as a source of energy, an improvement in efficiency of even just a few percent will have a major impact on our transport systems and environment.

A crucial factor in combustion affecting the efficiency of, and emissions from, engines is the temperature of the internal gas both before and after ignition. It has been notoriously difficult to measure this temperature with sufficient precision and accuracy since it needs to be done remotely without affecting the engine operation.

Research in Professor Paul Ewart’s group in Oxford’s Physics Department has overcome the main difficulties using a new method derived from their fundamental research in non-linear optics and laser spectroscopy. The technique uses two crossed laser beams to create a tiny hologram using the gas molecules in a flame or inside the engine. A third laser beam is reflected off the hologram and oscillations in this beam, caused by sound waves, are used to measure the temperature. The precision achieved is more than ten times better than the previous best method and has allowed subtle, but important, changes to be measured accurately.

In collaboration with Jaguar/Land Rover, BP and Shell, this new method is being used to improve the design of the next generation of engines and fuels, including bio-fuels. It is also providing data to inform improved computer models, developed in collaboration with theoretical chemists, that could lead to a reduction in combustion-generated soot particles that are harmful to health.
Did climate change help form our oil reserves?

Oxford geologist Dr Hugh Jenkyns studies rock formations to establish which ones are likely to have produced oil and why. Climate change appears to have played a role in their creation. His findings have helped the oil industry in their search for new oilfields.

In 1973, deep-sea drilling in the Pacific Ocean revealed black organic-rich sediments similar in age to those found in Italy, the UK, and many other parts of the world. This was an important discovery, because these sediments represent so-called ‘source rocks’—sources of oil. Further, the discovery suggested that source rocks are linked to discrete periods of geological time and are not, as previously believed, distributed across the Earth’s sedimentary strata.

Dr Jenkyns from Oxford’s Department of Earth Sciences and his American colleague, Seymour Schlanger, proposed that these unusual sediments were created during what they call an Oceanic Anoxic Event (OAE). During that time, oceans and seas were low in oxygen. This helped preserve the organic remains of plankton, which had fallen through the water column to become buried under the sea floor and would later turn into oil.

The impact of the OAE hypothesis has been significant. It offers oil companies additional insight when identifying and assessing potential source rocks during the exploration of new territories. This improves the odds of finding oil and reduces the cost of drilling in new sites.

Ironically, the deposition of our current oil resources, which are now linked to rising CO₂ levels, might itself have been the result of greenhouse gas induced climate change. It is generally thought that OAEs occurred when release of large quantities of greenhouse gases from erupting volcanoes caused the Earth’s climate to overheat. Local high rainfall might have stimulated the growth of plankton as a result.

Recent research by Jenkyns and Professor Gideon Henderson supports this hypothesis. They focused on calcium isotopes in OAE sediments in order to understand their chemistry, which points towards intense weathering of rocks on the continents due to high temperatures and abundant rainfall.

This research improves our ability to predict the presence of oil in rock formations, which still forms a critical part of our primary sources of energy.
The power of hot water tanks

Hot water tanks use a lot of energy, and many of them are operated inefficiently. Dr McCulloch has developed a sensor to detect and convey the level of hot water in a tank and thus improve operation and enable effective energy storage.

As renewable energy sources increase their share of energy output, energy storage and energy efficiency are going to become more important. This is particularly true of wind energy. Wind farms are able to produce significant amounts of energy, but the amount of energy that they create is highly variable and cannot be controlled.

The energy industry has traditionally adjusted supply to match demand. With substantial wind energy, demand will have to be matched to meet supply, according to Dr Malcolm McCulloch, University Lecturer in Engineering Science. A large amount of energy is used for central heating, refrigeration and hot water tanks. Dr McCulloch is interested in how energy can be stored and regulated in these three domains. His current focus is on hot water tanks, beginning with their use in homes.

Current hot water tanks operate inefficiently because they are unable to show the user how much hot water is available. Many users therefore use the ‘boost’ option to ensure they don’t run out of hot water during a shower. Often this boost is unnecessary and wastes energy.

The solution to this problem is to fix a sensor to the tank that will indicate how much hot water it has. Dr McCulloch and a doctoral student, Peter Armstrong, have developed such a sensor which is now under trial in a number of homes. The sensor works by recording the hot water level and therefore its volume. This is made possible because hot water is lighter and rests on top of the cold water. There is actually a fine boundary between the cold and hot water called a thermocline. This line remains intact until the tank is almost full of cold water.

The sensor is still at the prototype stage, but a number of companies have shown interest in its commercialisation.

It will prove to be particularly useful when novel energy tariffs are introduced over the next three to five years. Energy users will have a smart meter showing the different tariffs for different times of the day, so they will be able to decide when to switch on their appliances in order to minimise their costs. By varying the tariff, energy companies will be able to regulate demand. Consumers who have had a sensor fitted to their hot water tank will be able to use the energy in their tank much more efficiently and better regulate their demand. Therefore both energy providers and consumers will benefit from this sensor.

The next development for Dr McCulloch and Peter Armstrong will be to create a sensor for large-scale thermal stores.

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Can oil and gas migrate through rock?

Rock formations have sealed oil and gas reserves for millions of years. Professor Joe Cartwright identifies mechanisms by which oil and gas may bypass these seals. His work is important for the careful selection of drilling and CO$_2$ storage sites.

Oil and gas exploration is inherently risky, and considerable efforts are put into research designed to mitigate the risk of failure, which can be highly costly. One of the major risks is linked to the natural tendency for oil and gas to migrate upwards through layers that are usually considered as seals. It is important to quantify the natural leakage of hydrocarbons ahead of drilling a prospect or potential oil/gas field. Professor Joe Cartwright has spent much of his career as a geologist studying the factors that influence the degree of leakage of hydrocarbons in the subsurface.

A key part of his research is focused on the identification and physical characterisation of geological features that facilitate leakage—what he calls ‘seal bypass systems’. They commonly occur in geological layers that have an intrinsically low permeability, such as claystones, and which are generally viewed by the petroleum exploration companies as good seals or ‘caprocks’. Examples of these features include geological faults, and various types of intrusions, where a more permeable layer has been injected upwards under high-pressure and crosses the low permeable seal layer. Professor Cartwright’s research has enabled petroleum companies to recognise some of these potential leakage pathways in advance of exploratory drilling.

In particular, Professor Cartwright has discovered a new type of geological fault network that he has termed ‘polygonal fault systems’. 3D seismic imaging reveals their characteristic appearance, which is reminiscent of the cracks on dried out mudflats, and can be kilometres in length. They have the potential to substantially alter the sealing potential of geological layers. His research helps to clarify under what conditions polygonal faults form and what their impact might be on bulk permeability of a layer.

Professor Cartwright and his U.S. colleague, Professor Carlos Santamarina, have developed a theory that these faults are the result of chemical causes. Unlike the usual mechanical causes, these faults are believed to have formed as a result of reactions taking place during the first tens of metres of burial of the sediments—a process known as sedimentary diagenesis. Now they are testing the hypothesis that other fracture systems also result from sediment diagenesis, but the tests are not conclusive yet.

This research will have far-reaching importance not just for the oil and gas industry, but also for future applications such as the underground storage of CO$_2$, where the sealing properties of the caprocks are critical. This is arguably where this research could prove most beneficial.

For more information contact Joe.Cartwright@earth.ox.ac.uk or visit energy.ox.ac.uk/fossil-fuels/
Photosynthesis – can we do better?

Nature has converted sunlight into fuels for millions of years. Now University of Oxford researchers are developing processes that could allow us to produce hydrogen from sunlight by mimicking biological photosynthesis.

Sunshine is an abundant source of energy and great progress has been made in recent decades in converting it to electricity more efficiently and at lower costs. However, we still lack effective ways of storing the energy for when it is needed most.

For this we rely on fuels, like biomass or fossil fuels. These fuels also obtained their energy from sunlight, through the highly sophisticated and successful process of photosynthesis. Light-activated materials in plants, algae and some bacteria are able to absorb sunlight and create an electrical potential. Enzymes use this electrical energy to convert water and carbon dioxide into oxygen and storable chemicals such as sugars, which act as fuels for plants.

However, nature is more patient than man. Photosynthesis operates with modest conversion efficiencies of less than 2%. If we are to satisfy human energy demands, more efficient systems need to be developed. Can we do better than nature at converting sunlight into fuels?

Research in Professor Fraser Armstrong’s group in the Department of Chemistry is taking inspiration from photosynthesis. In particular, they focus on the enzymes which catalyse the reactions. Naturally occurring enzymes, such as hydrogenases, have evolved into efficient electrocatalysts, converting water into hydrogen and oxygen. Some enzymes achieve conversion rates that are orders of magnitude higher than conventional catalysts.

Genetically engineering enzymes helps Professor Armstrong’s group to better understand the intricate mechanisms behind such high efficiencies.

Using a suite of novel electrochemical techniques, including protein film electrochemistry, developed at Oxford, they investigate a range of practical applications, such as ‘hydrogen farms’ for which they optimise hydrogenases to enable micro-organisms to produce hydrogen photosynthetically. Another application is synthesis gas. Here enzymes are attached to semi-conductor nanoparticles to harness sunlight and convert water and CO$_2$ into hydrogen and carbon monoxide.

These insights into enzymes also help in the re-conversion of hydrogen to electricity. Novel biofuel cells using enzymes offer an alternative to precious metal catalysts, such as platinum, used in conventional fuel cells. The group has created an enzyme based fuel cell that can even produce electricity from low hydrogen levels in air.

The ultimate goal is to develop an artificial molecule from inorganic materials that matches the efficiency of natural enzymes. These ‘bio-inspired catalysts’ could improve the production of fuel from sunlight and also its re-conversion to useful energy, thus creating a truly renewable and storable fuel.

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Models to accelerate developments in solar photovoltaics

Oxford University physicists have achieved rapid improvements with novel photovoltaic materials. Behind their success lies the fundamental modelling of material properties carried out at the Mathematical Institute.

What can mathematical modelling contribute to the development of new-generation photovoltaic cells? Research headed by Professor Henry Snaith in the Department of Physics has shown that cells based on perovskite (an organo-metallic crystalline semiconductor material) have the potential to provide a cheap and efficient alternative to conventional silicon-based cells.

In the process of designing a cell, a large number of parameters need to be evaluated, all of which could affect the performance of the resulting photovoltaic cell. Although these parameters can be investigated experimentally, simply by altering various conditions and analysing the results, this can be time consuming. Rigorous mathematical modelling of the properties of materials can predict the conditions under which the performance of the perovskite solar cell will be optimised, and hence guide the direction of the experimental research.

Professor Alain Goriely and Dr Victor Burlakov at the Mathematical Institute have been working with Professor Snaith to model the processes involved in manufacturing perovskite-based photovoltaic cells, which are complicated by a number of factors. Perovskite is a difficult material to work with: it does not bond well to many substrates, and also does not wet well—the resulting paste tends to leave holes when screen-printed, potentially reducing the efficiency of the cell. In addition, it is difficult to predict its electronic properties.

When a photon strikes an atom in a semiconductor such as perovskite, it knocks free a negative electron that can move through the material, and leaves behind a positively charged ‘hole’ travelling in opposite directions to create a flow of current. If holes and electrons recombine, they create heat or light (photoluminescence), both unwanted effects since they waste charge that could be used to create electricity. The efficiency of the material is thus dependent on delaying or, ideally, preventing recombination of electrons and holes.

Goriely and Burlakov’s models have proved indispensable for finding the right processing parameters, such as film thickness, temperature and duration of annealing, to achieve a given level of perovskite film coverage for different substrates and conditions. This work has built on models of how liquids disperse on hard substrates (a classical problem in physics).

They further optimised processing parameters and improved cell efficiency by ensuring that the desired form and structure of films can be achieved. The fundamental understanding of the electronic properties of perovskite materials, especially the origins of photoluminescent effects, is used to minimise recombination and improve power conversion.

The mathematical modelling provided by Goriely and Burlakov has been instrumental in the rapid and dramatic improvements of the perovskite cells’ efficiency and stability, which has accelerated the development towards commercialisation through the University’s spin-out company Oxford Photovoltaics.

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Assessing the tidal power potential in the Pentland Firth

The UK has one of the best tidal energy resources in the world. Professor Thomas Adcock and his group are calculating the potential contribution of tidal energy towards our future energy mix using sophisticated flow models.

The strait between mainland Britain and the Orkney Islands, known as the Pentland Firth, is probably the most promising location for tidal stream energy anywhere in the world. Numerous claims have been made about how much energy the site might be able to produce based on a variety of methodologies. Professor Thomas Adcock and his Oxford Tidal Energy Group are informing the debate by deriving an upper limit on the power potential.

To understand the tidal dynamics in the region they developed a numerical model to seek the optimal amount of energy recoverable. Consider first the case when no turbines are installed in the channel: the velocity of the current in the strait will be the maximum but no power is extracted. Conversely, if you place too many turbines in the flow the current stops and again no power is generated. The optimum is clearly somewhere in between.

Professor Thomas Adcock and his team modelled this optimal point regardless of the type of turbine. For the Pentland Firth they estimate the resource to be about 5 GW averaged over time.

Unfortunately, this is far more power than could be generated in practice for two reasons. Firstly, tidal stream turbines have inherent inefficiencies. Energy is lost as the fast flow passing around the turbine mixes with the slower flow through the turbine. This is modelled with an approximation for the energy lost in the wake for a turbine of a given size and thrust.

The second inefficiency comes from the slowing of the flow caused by neighbouring devices. The more turbines are placed in the stream, the less effective each additional unit becomes. At some point adding further devices is no longer viable. One possible criteria is to set the cut-off point where the energy extracted per area swept becomes less than for off-shore wind. At this point, one might rather install wind turbines instead of more tidal devices, potential differences in cost notwithstanding. Based on this assumption, the modelling suggests an upper limit to power generation from the Pentland Firth to be around 1.9 GW—about half the electricity needs of Scotland.

In reality the power produced will be considerably lower. Turbines are not as efficient as the idealised model assumes. The power will also be intermittent—not just on a daily basis but also over the fortnightly spring/neap tidal cycle. Professor Adcock estimates that a tidal farm would generate eight times as much power in a day at spring tide than during a neap tide. On the plus side, these variations are predictable far in advance.

Thus, a significant amount of power can in theory be generated from the Pentland Firth. Recent comparisons to Saudi Arabia may be a little over-optimistic and Professor Adcock’s work provides important guidelines to manage the expectations for this new energy resource.

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Controlling Formula 1 cars efficiently

Sophisticated control systems are helping modern cars to become more fuel efficient. Oxford Professor David Limebeer pioneers mathematical models to take full advantage of new energy recovery systems in Formula 1 cars.

From 2014, Formula 1 has introduced a strict 100kg limit on the fuel used per race, down from 160kg the previous year. This restriction is one of the most substantial changes in the history of motorsport, and has forced Formula 1 designers to develop innovative ways to improve efficiency. The results are some interesting fuel-saving and power-generating technologies.

The kinetic energy a car loses when braking is usually irreversibly lost as heat. Now Kinetic Energy Recovery Systems (KERS) are able to convert this energy into electricity, store it in batteries and release it again when the car accelerates, or to provide a boost during overtaking. The new Formula 1 regulations have seen the capacity of KERS double to 120kW, and the battery capacity has had to increase tenfold as a result. A second system recovers energy from the exhaust, where around 70% of the energy is lost as heat. Some of this heat can be captured and converted into useful energy to drive the car.

These systems now make a fundamental contribution to the power of Formula 1 cars, which poses new challenges for the control systems managing the energy allocation during braking, cornering and accelerating. When and in what proportion should energy be drawn from fuel or released from energy recovery systems? When should energy be stored? These decisions need to be taken in real time, without impacting the driver.

This is where Professor Limebeer’s research is critical. His group develops computer-based mathematical models that incorporate the various parameters. Their control system takes the physical properties and limitations of the different power sources into account, as well as road conditions and aerodynamics.

The algorithms of Professor Limebeer’s group help to control the new devices and also act as a teaching tool in car simulators, where changes to parameters can be tested without the need to build expensive prototypes. This helps the Formula 1 teams to ensure that the car stays within its physical limits, delivers optimal performance and complies with the efficiency regulations.

The advanced control systems adopted in Formula 1 are increasingly relevant to road cars as well. Some buses already use KERS and racing teams are translating their R&D to passenger vehicles where they help to improve fuel efficiency, without the driver even being aware of the complex decisions being taken by these systems on their behalf.

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Making emission reductions attractive across borders

New trade arrangements could deliver much needed global emission reductions. Professor Hepburn and colleagues use game theory to show how unilateral actions on border carbon adjustments may deliver global results.

Years of international climate change conferences have done little to address the continuing rise in greenhouse gas emissions. Despite the widespread agreement on the need for action and a patchwork of efforts around the world, global emissions have not even been dented since 1990. An international agreement remains out of sight and unilateral action is not attractive for today’s large emitters for fear of putting themselves at a trade disadvantage.

Professor Hepburn and colleagues have analysed arrangements that could turn these dynamics on their head. Border Carbon Adjustments (BCA), which change the focus from production to consumption based emissions, may hold the key to unlocking the current stalemate in climate negotiations. These arrangements could avoid trade distortions and lead markets towards convergence on a global carbon price, even if adopted unilaterally to begin with.

Under present arrangements some governments impose a tax or issue tradable permits on domestic emissions, while others still subsidise fossil fuels. The resulting imbalances in the effective price of carbon distort trade and lead to an undesirable side effect called ‘carbon leakage’. Domestic production is put at a disadvantage relative to countries with a lower or even negative price on carbon emissions. Fewer goods are exported, while emissions through imported goods rise. Thus, the local economy suffers and globally little has been achieved. Not surprisingly, governments are reluctant to take strong unilateral action.

This is where BCAs could provide a better solution. Permits are based on emissions at the point of consumption, creating a level playing field between imported and domestic emissions. Domestic ‘clean’ producers are protected and the prospect of collecting revenue from imported emissions would make BCAs more attractive to governments.

BCAs could even be phased in unilaterally, without the need for a Kyoto-style global agreement, and initially only in selected carbon-intensive sectors. Once this first step has been taken, virtuous cycles could result. Professor Hepburn’s game theoretical models suggest that the presence of a BCA in one market creates a desire among its trading partners, facing export duties, to apply carbon adjustments themselves. An incentive to participate, rather than to abstain, has been created.

The arrangements are in principle compatible with WTO’s rules. In fact, welfare is increased by avoiding losses from environmentally damaging trade.

The work of Professor Hepburn and other Oxford economists could thus open up new ways to reach global emission reduction targets in an economically balanced and politically practical and pragmatic manner.

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Confining turbulent fusion plasmas

Research by Professor Alex Schekochihin, Felix Parra, Michael Barnes and colleagues on the fundamental physics of plasmas is accelerating the possible advent of nuclear fusion as a viable large-scale sustainable source of power, as well as improving our understanding of galaxies and stars.

Plasma, the state of matter comprising a high-energy mixture of free electrons and free nuclei, exists throughout the universe. Plasma is the state of matter in stars and the solar wind, and is used in man-made electronic applications such as fluorescent lighting and plasma screen TVs.

Fusion between nuclei of deuterium and tritium (two different types of hydrogen) can occur in a plasma at temperatures that are high enough to overcome the electrostatic repulsion between the two positively charged nuclei – typically 200 million degrees Celsius. The raw fuels that are used to produce tritium and deuterium are lithium and water: used in a fusion power plant, the lithium in a single laptop battery and half a bath of water would provide the UK’s per capita energy output for 30 years. This makes reliable and economically competitive fusion power a potential holy grail in the search for low carbon energy.

It is necessary to master many difficult fundamental science and engineering challenges in order to create and sustain the correct conditions for fusion to occur in plasma confined in magnetic “bottles” known as “tokamaks”. A confined fusion plasma is an inherently turbulent system, with the plasma consisting of chaotic motions and eddies on many different scales. Understanding turbulence, and the turbulent transport of energy and momentum, are among the most challenging problems in plasma physics. Reducing the turbulence will lead to smaller, cheaper and therefore more cost effective reactors. The Oxford Plasma Theory group led by Professor Alex Schekochihin works on understanding and modelling the fundamental processes that control how heat, particles and momentum are transported in the plasma and how they therefore resist confinement.

Fusion plasmas confined in tokamaks exhibit several different “modes” of behaviour, each with different properties. Certain conditions of the plasma known as H-modes, in which turbulence is suppressed and the plasma has a sharp well-defined boundary, produce a very helpful increase in the rate at which fusion occurs. Currently, we have no convincing theory of what produces the H-mode, or what causes spontaneous shifts between the H-mode and other, less desirable, modes of operation.

Working with staff at the UK’s fusion research centre located nearby at the Culham Laboratory, which houses both the UK (MAST) and European (JET) tokamaks, Oxford physicists have exposed the critical role played by plasma rotation and outlined a possible pathway towards optimising fusion reactors.
Interactions between tidal flows and the turbines extracting power from them are complex. Professor Richard Willden and his team are working on models to optimise efficiency, and have identified ways to surpass conventional theoretical limits.

Imagine you have just bought yourself a few tidal turbines. Where should you put them? Would it be best to find a wide channel and spread them evenly across its width, or should they be placed closer together, perhaps occupying only part of the channel width? If you had to allow room for shipping lanes, how much power might you lose? Some surprising answers to these questions have emerged from Professor Richard Willden’s research on the efficiency limits of tidal turbines.

Professor Richard Willden and colleagues have developed new models that build on sophisticated flow models for tidal turbines in order to estimate their efficiency, impact on tidal flows and interference with each other, independent of the specific turbine design. The challenge is to optimise the performance of turbines by getting them to sweep as large a cross section of the tidal flow as possible, without causing the flow to unduly bypass the turbines or to be redirected to a different channel altogether.

Unlike wind turbines, which can often be arranged in distributed farms, tidal turbines are best arranged along a line perpendicular to the direction of the tides. Any turbines placed in a second row would produce less power – an effect known from wind turbines, but much more pronounced in tidal streams. How should tidal turbines best be distributed along this single line?

For a given number of turbines, an intuitive solution might be to space them evenly and widely to take advantage of as much tidal stream as possible, and to prevent turbines from interfering with neighbouring ones. However, Professor Richard Willden’s model suggests that clustering the turbines could enhance their energy generation potential.

The Lanchester–Betz limit stipulates that, even in an idealised model, individual wind and tidal turbines can at most extract the energy equivalent to 59.3% of the kinetic energy from the fluid passing through them. By bringing the turbines closer together, this limit can be significantly exceeded. The model shows that even in the case of an infinitely wide channel, the theoretical limit can be increased to as much as 79.8%, if the spacing between turbines is optimised, and by far more if the channel width is not too large.

Instead of placing the turbines across a channel, it is therefore advantageous to place a group of them in a cluster. This gives the added benefit of reducing connection costs between turbines, as well as making the shipping channel a natural by-product of the installation, rather than a planning constraint.

Given that the costs of early tidal turbines are still high, their optimal placement could prove crucial for the advancement of this nascent technology option.

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Children growing up today are becoming the first truly “digitally native” generation, with constant access to information and social media. This transformative change opens up wide reaching challenges and opportunities for business models in the energy industry. Distribution Network Operators are particularly able to benefit from new forms of consumer engagement and the available intelligence to better manage future systems.

The 2014 floods in the UK highlighted the importance of fast response capabilities to restore power to consumers. In order to become more proactive in their engagement with consumers, Professor Grindrod is developing algorithms that could help network operators to tap into the wealth of information from social media channels.

Presently network operators rely on consumers ringing their call centres to report faults or emergencies. The next generation of customers will simply reject this mode of communication. DNOs will instead be able to gather intelligence more cheaply and more effectively through social media.

Professor Grindrod’s mathematical models are able to extract critical information and trends from media channels, such as Facebook and Twitter. Even seemingly unrelated messages can reveal important information that, if interpreted correctly, gives network operators valuable intelligence to anticipate exceptional energy demand situations and emergencies.

The frequency, nature and geographical location of messages can channel response resources immediately to where they are needed.

The communication works the other way as well. By engaging with this new generation of prosumers through social media, network operators can meaningfully provide information not only during emergencies, but also on a day-to-day basis to better manage supply and demand.

The lifestyles of the next generation of energy users will demand ever more reliable energy provision, to support their highly interconnected lifestyles. Conventional mail and call centres will no longer do. Professor Gridrod’s work helps DNOs to listen to customers better and to respond to their needs by intelligently interpreting the information they willingly provide about their everyday lives.

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Understanding the chemistry of elements involved in the nuclear fuel cycle is crucial for ensuring the safe storage of nuclear waste, and for improving the reprocessing of used nuclear fuel, which allows Uranium to used more efficiently and reduces the volume of waste that needs long-term storage.

Professor Steve Faulkner and his group work on the fundamental chemistry of the Lanthanide and Actinide elements, especially Uranium and Plutonium. The properties of these elements govern their mobility in water and the processes involved in separating different components of used fuel.

The reactivity and mobility of nuclear waste are of upmost concern when considering safe storage. Understanding which waste species are mobile in groundwater is crucial for preventing potentially dangerous leakage and contamination. Work by Prof. Faulkner’s group on establishing the nature of mobile waste species and establishing how apparently immobilized ions can be converted into species that travel through groundwater is integral to this. Research on the spectra and photophysical properties of the Actinides is improving understanding of the form and oxidation state of the mobile species.

Small leakages of radioactive material into the natural environment can have large consequences over time. Developing a reliable method to detect very small amounts of fuel-cycle material is vital both for the safety of nuclear power plants and for nuclear waste disposal. Oxford Chemists are helping the National Nuclear Laboratory to improve the ability to detect very small quantities of materials by developing molecules that bind Actinides and, in the process, become luminescent when exposed to ultra-violet light. In the case of neptunium, environmental detection can be achieved at concentrations up to seven orders of magnitude lower than observable by current radiometric methods.

There are concerns that there might be a shortage of cheaply available Uranium within a couple of generations if use of nuclear energy expands rapidly. Reprocessing used nuclear fuel to extract fissile Plutonium and Uranium, which can then be re-cycled as fuel, allows Uranium to be used more efficiently, and can radically reduce the volume of waste that needs long-term storage. Twice-through fuel cycles can improve the efficiency by some 20%. Fast breeder reactors use fuel some 60 times more efficiently than conventional reactors, and can burn long-lived waste. Separating Uranium from the minor Actinides is not straightforward, in particular because Neptunium and Uranium have very similar properties. Research in Oxford on the chemical composition of nuclear fuel and the waste streams is helping to make reprocessing more efficient.

By understanding the chemistry of the nuclear fission fuel-cycle elements and their interaction with the environment, Oxford chemists are helping to build a safe and more efficient nuclear future.
Structural materials in nuclear reactors

New nuclear reactor concepts promise more efficient fuel use and to reduce high-level nuclear waste, while structural demands on materials become more stringent. Professor James Marrow’s research improves methods for measuring the damage and longevity of materials.

With increasing world energy demands and climate change, there is pressure to develop sustainable energy technologies. Nuclear energy can contribute; in 2013 Nuclear fission provided 11.7% of the world’s electricity, behind hydro power (16.3%) but well ahead of all other low carbon sources. However, although light water reactor (LWR) nuclear fission is broadly a low-carbon technology, breakthrough technologies are needed now to secure the long-term future of nuclear power. Fast neutron reactors with closed fuel cycles can reduce levels of high-level waste and contribute to more efficient use of uranium resources, which will be under pressure with an expansion of the LWR fleet. Certain fast reactor concepts have process heat applications, which can support economical hydrogen or synthetic hydrocarbon fuel production. The advanced nuclear fission plant concepts are referred to as “Generation IV” systems, and are intended to be in operation as commercial plant by the middle of the 21st Century.

The operating conditions of the Generation IV concepts will place significant demands on their structural materials, far more stringent than those for existing nuclear plant. In the longer term, nuclear fusion offers sustainable energy production without the issues of long-lived radioactive waste and nuclear proliferation that accompany fission; however, there remain very significant engineering challenges to be overcome. For the lifetimes of current reactors to be safely extended and also to inform the materials selection and design of future reactors, understanding of the mechanisms of deformation and damage are of great importance.

Professor James Marrow’s research into this area is directed towards improving methods for measuring damage in the microstructure of materials, using three-dimensional imaging to validate and develop predictive models. Focusing on graphite, the material used to moderate neutrons in gas-cooled reactors, Professor Marrow has examined the formation and propagation of microscale cracks which may shorten the lifetime of the material, providing data to inform modelling on the engineering scale. This information is being used, in conjunction with both industrial partners and industry regulators, to better understand the structural integrity of nuclear components. His approach is now finding further applications in new materials, such as ceramic composites, that will be needed in future nuclear fission and fusion reactors. The analysis is extendable to a wide range of materials, including bone and bone replacements and composite materials for energy efficient transportation.

Oxford is uniquely placed to lead research in this field due to the availability of a wide variety of experimental techniques across several departments. Research at Oxford also benefits from close collaborations with the Diamond Light Source synchrotron facility and researchers within Europe engaged in the development of structural materials for nuclear fusion and fission power.

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