ingenia

MARCH 2019 ISSUE 78

LIGHT DATA TRANSFER
BIOFUELS FOR TRANSPORT
LIQUID AIR ENERGY STORAGE
EFFICIENT POWER CONVERSION
GROWING FOOD CROPS IN TRAYS

ROYAL ACADEMY OF ENGINEERING

www.ingenia.org.uk

ROYAL ACADEMY OF **ENGINEERING**

Sponsors

The Royal Academy of Engineering acknowledges the generous support of the following organisations for *Ingenia*:

- Arup
- BAE Systems

Published by the Royal Academy of Engineering
Royal Academy of Engineering,
Prince Philip House, 3 Carlton House Terrace, London SW1Y 5DG
Tel: 020 7766 0600 Website: www.raeng.org.uk Email: editor@ingenia.org.uk

Registered charity no. 293074

With thanks to
Andy Coulson (proofreader)

Ingenia welcomes proposals and suggestions for articles that aim to stimulate readers from both within and outside the engineering community. The writing style should be clear, authoritative and easy for non-specialists to digest. Prospective authors should submit a one-page outline to the Managing Editor, the Editor-in-Chief or to any member of the Editorial Board.

Ingenia online can be found at **www.ingenia.org.uk**

Design
The Design Unit www.thedesignunit.com

Print
Pensord www.pensord.co.uk

Ingenia magazine is recyclable. The cover is treated with a recyclable laminate, the inks are vegetable oil based and the paper produced under Forest Stewardship Council guidelines.

Advertising and sponsorship
Gemma Hummerston
Tel: 020 7766 0679 Email: gemma.hummerston@raeng.org.uk

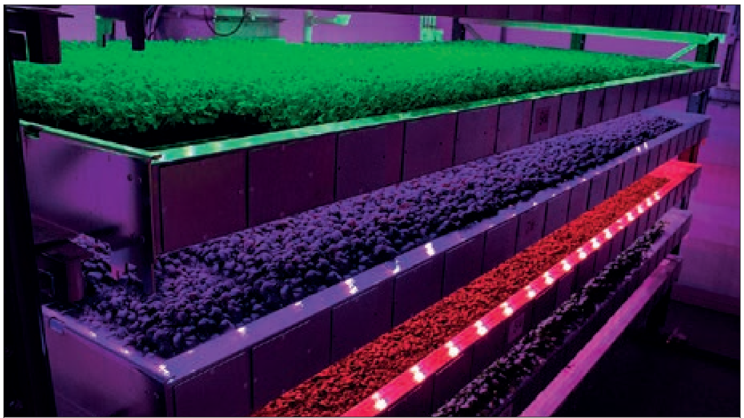
Subscriptions
To cancel your subscription or update your personal information details, please contact the *Ingenia* team by sending an email to ingenia@raeng.org.uk

Front cover
A crop is grown indoors under LED lights at the James Hutton Institute in Dundee
© Intelligent Growth Solutions

ISSN 1472-9768

Royal Academy of Engineering promotes excellence in the science, art and practice of engineering.

Biofuels' journey to the mainstream p12



Farming for future growth p18

How I got here p8

Efficient semiconductors p24

New contender for energy storage p30

Role model for next generation p41

CONTENTS

UP FRONT

FEATURES

PROFILE

@RAEngNews #IngeniaMag


THIS IS ENGINEERING
FASHION SPACE BIG STUFF ENTERTAINMENT SPORT
FOLLOW WHAT YOU LOVE INTO ENGINEERING
THISISENGINEERING.ORG.UK
THIS IS ENGI NEER ING

EDITORIAL

FOCUS ON PHYSICS

Dr Scott Steedman

The UK needs 124,000 engineers and technicians every year to meet industry needs.

In the 2018 edition of its excellent report *The state of engineering*, EngineeringUK predicts an annual shortfall of nearly 50% in meeting this target. This challenge is not new. In 2012, the Royal Academy of Engineering's report *Jobs and growth* recognised a similar shortfall. Professor John Perkins CBE FREng, then Chief Scientific Adviser at the Department of Business, Innovation and Skills, reported in his 2013 *Review of Engineering Skills* that businesses were having to 'make do' with talent from other disciplines or from abroad.

A critical issue for the engineering profession in the UK is that too few women choose engineering as a career. EngineeringUK's 2018 report suggests that only around 12% of those working in engineering or related roles are female. This is at the bottom of the league table of European countries, where percentages closer to 20% are more common.

Studies show that young people are lost to engineering at each successive stage during their higher and further education. Perkins described this as a 'leaky pipeline' of talent that the nation could ill afford to lose. He made a series of recommendations aimed at encouraging young people to stay with engineering.

In January this year the Academy published a follow up to the 2013 Review, again led by Professor Perkins and supported by the wider professional engineering community. The 2019 report, *Engineering skills for the future*, recognises that there has been good progress in some important areas, such as the extraordinarily successful *This is Engineering* campaign on social media (see 'This is Engineering!' *Ingenia* 74). *This is Engineering* has now notched up more than 30 million views in the target age group of young people since January 2018. In addition, commitment from government and support from industry have transformed technical and vocational education, with substantial apprenticeship reforms, new T-level technical qualifications set for delivery in 2020 and new content in the GCSE curricula for computing and design and technology.

Yet one particularly fundamental barrier remains. The proportion of students studying A-level physics has risen slowly since 2012, from 7% to 8% of the annual cohort of boys and from 1.6% to 1.9% of girls, but these percentages remain well below the numbers for A levels in biology or chemistry. The continuing shortage of specialist teachers is an important factor and too few schools have suitably qualified physics teachers, but cultural issues among young people and their parents also affect the choice of A-level subject.

The good news is that last year maths was the most popular A-level subject in the UK and a healthy proportion (39%) of candidates are female. Down in the mid-ranks, physics sits alongside geography in popularity, ahead of sociology and behind art and design.

What sets A-level physics apart from these other subjects, including biology and chemistry, is that it is dominated by boys. Fix that: get girls into physics, and a significantly larger and more diverse pool of talent will open up that may become inspired to choose engineering as a career.

The profession has done much of the homework already. The report from the Institution of Mechanical Engineers, *Five Tribes: Personalising Engineering Education*, published in 2014, described the different audiences that need to be reached. More than 600 organisations are running initiatives to inspire young people and interest them in a scientific or engineering related career, so there is no shortage of volunteers (although there is an urgent need for more coordination). The introduction of a 'careers leader' in schools in England as part of the *Careers Strategy* published in 2017 by the Department for Education is also a welcome development.

However, above all our campaigns and communications should focus on physics. With the exception of physics, science subjects have successfully attracted female students. Making physics as attractive for girls as biology or chemistry could deliver rapid success, even break the mould, as *This is Engineering* has demonstrated can be done. The sky is the limit. Look no further than the recent announcement of the promotion of Air Marshal Sue Gray CB OBE FREng, to become the most senior female military officer in the British Armed Forces (see page 41), to see what's possible when inspiration calls.

Dr Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

GPS PIONEERS RECEIVE GLOBAL ENGINEERING PRIZE

QEPrize winners Hugo Fruehauf, Professor James Spilker, Dr Bradford Parkinson and Richard Schwartz (L–R) with HRH The Princess Royal (third left) and Lord Browne (second from right)

The four engineers responsible for creating GPS won the 2019 Queen Elizabeth Prize for Engineering (QEPrize). The four winners, Dr Bradford Parkinson, Professor James Spilker, Hugo Fruehauf and Richard Schwartz, were awarded with the prize for their pioneering work that has given free, immediate access to position and timing information to over four billion people around the world. The announcement was made by Lord Browne of Madingley FREng FRS at the Royal Academy of Engineering on 12 February, in the presence of HRH The Princess Royal.

The QEPrize is an international £1 million prize that celebrates the engineer or engineers responsible for a groundbreaking innovation that has been of global benefit to humanity. Its objective is to raise the public profile of engineering and to inspire young people to become engineers.

GPS's applications range from navigation and disaster relief to climate monitoring systems, banking, transport, agriculture, and industry. It uses a constellation of at least 24 orbiting satellites, ground stations and receiving devices. Each satellite broadcasts a radio signal containing its location and the time from an extremely accurate onboard atomic clock. GPS receivers need signals from at least four satellites to determine their position; they measure the time delay in each signal to calculate the distance to each satellite, then use that information to pinpoint the receiver's location on earth.

As the chief architect, Dr Parkinson is often called the 'father of GPS' after he successfully built upon several separate systems to create the current GPS design. His insistence that GPS should be intuitive and inexpensive made navigation accessible to billions.

Dr Parkinson recruited Professor Spilker to design the signal that the satellites broadcast, which is resistant to jamming, is precise and allows multiple satellites to broadcast on the same frequency without interference. Professor Spilker's team also developed and built the first receiver to process GPS satellite signals.

GPS receivers rely on accurate timing information, broadcast from satellites, to determine their position on earth. Hugo Fruehauf, then the chief engineer at Rockwell Industries, led the development of a miniaturised, radiation-hardened atomic clock that became the GPS 'clock of choice'. Its accuracy is the backbone of communications systems, power grids, financial and trade networks, and other critical infrastructure.

For GPS to be affordable, each satellite had to be longlasting. Richard Schwartz, the programme manager at Rockwell during the development of the satellites, was tasked with ensuring a three-year lifespan. His design was resistant to intense radiation and lasted over nine years.

The winners were decided by an international panel of judges, chaired by Professor Sir Christopher Snowden FREng FRS. As well as the £1 million prize, the winners will each receive a trophy at a ceremony later this year. The 2019 trophy was designed by 16-year-old Jack Jiang from Hong Kong, winner of the international Create the Trophy competition.

More information about the prize and winners can be found at **www.qeprize.org**

NEW ENGINEERING ENGAGEMENT PROJECTS LAUNCHED

Through its public engagement grant scheme, *Ingenious*, the Royal Academy of Engineering is funding 27 new projects that will allow engineers to engage the public in innovative ways.

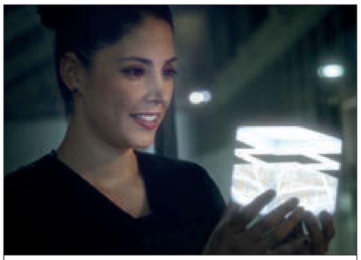
The projects will provide engineers with the opportunity to engage public audiences with creative engineering content and also build their engagement skills. They will reach diverse and underrepresented audiences across the UK and provide opportunities for members of the public to meet professional engineers and learn about the exciting, creative work that they do.

The 2019 projects include the Ingenious Circus, a project run by the University of Glasgow that brings engineers and circus performers together to develop a workshop for schools. Engineering the human body will show children in Manchester the role that engineering plays in healthcare through a series of workshops and challenges based on tissue engineering and personalised medicine. In Wales, engineers will explore the engineering heritage of the Pontcysyllte Aqueduct and canal, and connect the history to current engineering projects.

Ingenious is supported by the Department for Business, Energy and Industrial Strategy. A full list of projects funded by the scheme can be found at **www.raeng.org.uk/ingenious**

Young people take part in a design and engineering camp run by FixCamp, an *Ingenious* awardee in 2018 © FixEd 2019

YOUNG WOMEN ENGINEERS RECOGNISED



Daniela Paredes, who has appeared in the *This is Engineering* campaign, received a Women in Innovation Award for Gravity Sketch's virtual reality design tool

Nine young women innovators have been awarded with £50,000 each as part of Innovate UK's Women in Innovation Awards.

Announced on International Women's Day on 8 March, the winners were recognised for their pioneering innovations that are tackling some of society's biggest challenges, as set out in the government's industrial strategy.

The winners include Royal Academy of Engineering Enterprise Fellow Sheana Yu, Founder and CEO of Aergo, who is developing a device to be built into wheelchairs that monitors movement and automatically inflates and deflates air cells to ensure better posture and comfort. Another recipient is Daniela Paredes, who featured in season one of the *This is Engineering* campaign. Daniela is Co-Founder and Director of Gravity Sketch, which has developed a virtual reality design tool.

As well as the funding, all the winners will receive a year-long package of bespoke support, coaching and mentoring, and a commemorative plaque that will be installed where each woman's innovation journey began.

Innovate UK Executive Chair Dr Ian Campbell said: "Innovate UK's Women in Innovation Awards address a key barrier for diversity in innovation – a lack of female role models. By recognising their achievement with purple plaques, we are making sure that our nine newly crowned winners inspire the next generation of female innovators.

"Whether it's inspiring young students showing a passion for STEM, someone with the spark of an idea, or an innovative business ready to be taken to the next level, the Women in Innovation 2019 campaign aims to drive long-term, far-reaching positive change."

THIS IS ENGINEERING SEASON 3

This is Engineering has launched a new season of films that feature four young engineers working in a range of industries, from robotic farming to sustainable cosmetics.

The four new engineers include Halvard, a robotics engineer who has followed his love of nature into creating robots to revolutionise farming. Jahangir works for the BBC as a broadcast engineer and Olivia, who was always interested in sustainability and is a chemical engineer at Lush (see 'How I got here', *Ingenia* 75). The final engineer is Sophie, who always wanted to become an astronaut – she realised that engineering was the route to space, and now works at BAE Systems on the high-speed planes of the future.

This is Engineering was created in response to significant demand for engineering talent in the UK and narrow public perceptions of engineering and engineers. The campaign launched in January last year and the first two series of films have been viewed more than 30 million times by teenagers on social media.

***This is Engineering* protagonist Olivia Sweeney sources aroma chemicals to create fragrances at cosmetics company Lush**

FIRST VEHICLE TO BREAK SOUND BARRIER RECEIVES AWARD

The Thrust SSC is currently on display at Coventry Transport Museum

The British-designed Thrust supersonic car (SSC) has been awarded the Institution of Mechanical Engineers' (IMechE) Engineering Heritage Award. It was the first land vehicle to break the speed of sound.

In 1997, the 54-foot-long Thrust SSC broke the sound barrier at the Black Rock Desert in Nevada. The car set the record by burning 18 litres of fuel a second to reach a speed of 764 miles per hour. Twin Rolls-Royce Spey turbofan engines powered the vehicle with 50,000 pounds of thrust.

John Wood, chair of the IMechE Engineering Heritage Award, said: "When it comes to individual artefacts, it's not an easy decision to make and our aim is always to ensure that only the very best and unique are honoured by the award. The vehicle and the team behind it were working in completely unchartered territory and what they achieved was quite extraordinary. We are very pleased to honour this vehicle with this award and hope it inspires the young engineers of the future in particular to head to the museum to see it in all its glory."

Established in 1984, the awards aim to promote artefacts, sites or landmarks of significant engineering importance from the past and present. This is the 125th Engineering Heritage Award to be presented, and previous awards include Alan Turing's Bombe at Bletchley Park, the E-Type Jaguar and Concorde.

STUDENTS ADDRESS GLOBAL CHALLENGES

Students have been invited to put forward an innovation that addresses the global challenges presented by a growing population and new technological changes.

As part of the Global Grand Challenges Summit 2019 (GGCS), teams from UK, Chinese and US universities will demonstrate an innovation that is viable and will have sustained impact. Five teams from each country will be chosen to pitch their innovations on the first day of a three-day Collaboration Lab, which precedes the summit. They will present a three- to five-minute pitch of their proposals to a selection of senior judges and all Collaboration Lab event participants. The winning team will receive a small cash prize.

The summit is a collaboration between the UK, US and Chinese academies of engineering, which will take place in London, hosted by the Academy, between 16 and 18 September.

The event will bring together world leaders with the next generation of engineers to build collaborative solutions for our future world. The summit is based around the theme of *Engineering in an unpredictable world*, with subthemes of 'Can we sustain 10 billion people?' and 'Will AI and other transformational technologies change humanity for the better?'.

Dr John Lazar CBE FREng, chair of the steering committee for the summit, said: "Our overriding ambition is to generate lively discussion and rigorous thought on the huge challenges facing humankind over the next three decades. In particular, we want to extend horizons for younger engineers, so they can explore how to tackle the grand challenges and UN Sustainable Development Goals, working in an open and cross-disciplinary fashion."

For more information about the competition and summit, visit **www.ggcs2019.com**

GAUDÍ'S LA SAGRADA FAMÍLIA IN THE MAKING

Gaudí's La Sagrada Família will be completed using digital engineering techniques

On 23 May, the Royal Academy of Engineering will host a talk by Tristram Carfrae FREng, Deputy Chairman of Arup, in which he will discuss the modern engineering techniques being used to complete Antoni Gaudí's famous La Sagrada Família church in Barcelona.

The construction of La Sagrada Família began in 1882. However, one year later, the original architect resigned and Gaudí was commissioned to redesign the Basilica. He worked on the project for 43 years, until his death in 1926.

This lecture will cover the history of the church's design and construction, concentrating on the six main towers: the highest points of the Basilica. During the 19th century, construction of the church was largely carried out in conventional stone masonry, with recent work using reinforced concrete and stone facing. However, the design of the remaining 40% of the Basilica, due for completion in 2026, will use pre-stressed stone panels. New digital methods and traditional craftsmanship will dramatically reduce the weight, cost and time needed to complete the Basilica. This talk will describe how this new technique evolved, including initial ideas, virtual prototyping, analysis, physical testing, production, and assembly.

To find out more and book tickets, please visit **www.raeng.org.uk/events**

HOW I GOT HERE

Q&A

DR ANH TRAN
HUMANITARIAN ENGINEER

Dr Tran studied chemical and biomedical engineering before becoming a humanitarian engineer

Dr Anh Tran is a humanitarian engineering researcher and lecturer at Coventry University. Her research focuses on energy, water, food, and computer technologies with resource-limited communities.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

My family has always encouraged higher education as a way to move up in life and my primary school teacher inspired my love of science through our lessons on space. I wanted to be an astronaut. In my first year of studying engineering at university, I realised that there were more problems on earth that needed solving than in space – challenges such as poverty alleviation and environmental degradation. Hearing about the hole in the ozone layer as I was growing up, I could see that engineering and technology could be part of the solution to the global challenges of our generation.

HOW DID YOU GET TO WHERE YOU ARE NOW?

I studied English, maths, physics, ICT and chemistry at school in Australia. At university, I studied chemical and biomedical engineering as I felt it was a people-centred engineering discipline. After that, I started a PhD in pharmaceutical engineering and then joined my local Engineers Without Borders (EWB) chapter. EWB encourages engineers to make a difference to people through exploring solutions to the most pressing global development issues. I volunteered in Cambodia for a year and then returned to Australia to work with EWB Australia leading the EWB Challenge, which is a design challenge for first-year university students to investigate how technology can solve problems in resource-limited settings. This was a hugely rewarding job that involved inspiring a new generation of engineers to see that their skills could be used in a humanitarian context. I then worked as a researcher, completed my PhD, and had a family before landing my dream job as a humanitarian engineer in the UK and becoming involved with the UNITWIN/UNESCO Network for Humanitarian Engineering. As the daughter of Vietnamese refugees my work on sustainable energy in refugee and host communities is very meaningful to me. It brings a sense of circularity to my career as an engineer.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

I have two career achievements that I'm proud of. First, working to develop the EWB Challenge and then becoming the first international coordinator. The project has now expanded from Australia and New Zealand to all across the world, including the UK. Second, I successfully secured a £1 million research project to investigate sustainable energy in refugee camps in Rwanda and Nepal.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

The endless possibilities of how engineering and technology can have an impact on our world, and particularly in low-resource settings. My favourite part is working as part of an interdisciplinary team to collaborate and co-design with communities to develop technological, social and business solutions to improve their quality of life.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

At the time of writing, I'm in Vietnam at the Royal Academy of Engineering Frontiers of Engineering Development (FoED) symposium discussing engineers' role as healthcare practitioners. Last week, I was in the US presenting at the IEEE Global Humanitarian Technology Conference and before that, working with Brazilian researchers on Internet of Things applications in agriculture for smallholder farmers in São Paulo, as part of an FoED grant. When I'm not travelling, I spend a lot of my time working collaboratively with my international partners using online communication tools. My top tip for working successfully on global research projects is a strong relationship with local partners who understand the local context and are experts in their domain.

WHAT WOULD BE YOUR ADVICE TO YOUNG PEOPLE LOOKING TO PURSUE A CAREER IN ENGINEERING?

Engineering is diverse and there are many opportunities to apply science, technology, design, social science, and business solutions to solve the global challenges we face today. Follow your passion and hopefully someone will pay or fund you to do it. I especially encourage young, aspiring women and those from minority backgrounds to pursue a career in engineering, as voices from different backgrounds enrich engineering and bring new ways of thinking.

QUICK-FIRE FACTS

Age: **30s**

Qualifications: **Bachelor of Chemical Engineering with Biomedical Minor (Honours), PhD in Chemical Engineering.**

Biggest engineering inspiration: **Professor Peter Guthrie OBE FREng at the University of Cambridge. In 1980, he founded the Register of Engineers for Disaster Relief (now RedR) following his experiences working in refugee camps during the Vietnamese refugee crisis.**

Most-used technology: **My mobile phone, laptop and internet connection – my office in a bag.**

Three words that describe you: **Passionate, curious and a friend once described me as a "ball of fire with hair" – sounds about right.**

WHAT'S NEXT FOR YOU?

I'm working on a number of research projects. As a member of Global Plan of Action for Sustainable Energy Solutions in Situations of Displacement – a framework that aims to progress safe access to affordable, reliable, sustainable, and modern energy services for all displaced people by 2030 – I'm supporting Sustainable Development Goal seven (affordable and clean energy) for refugees and host communities through my research. I'm also collaborating with Australian researchers to develop a low-cost tsunami early warning system in the Indo-Pacific region that doubles as a community radio station and education tool.

Testing water for arsenic in Cambodia

OPINION

IS ENGINEERING PRODUCTIVE?

The way in which productivity is measured in the UK does not account for advances in engineering and what these have added to GDP. However, a new group of statisticians, engineers and economists are working to change this and ensure that productivity is measured properly. Professor Will Stewart FREng argues that engineers also have a part to play in promoting engineering's role in greater productivity.


Professor Will Stewart FREng

To many engineers it is absurd to question the notion that engineering adds to our productivity. Over the past 30 years communications engineers have developed systems that deliver some 100 million more bits to your smartphone per pound spent. Lighting engineers can also point out that a modern LED lamp delivers light 10,000 times more cheaply than a candle. So, it will come as a shock to many engineers that national figures for productivity and GDP have not reflected these advances. Indeed, by some counts, these engineering developments may actually have made things worse.

The cause of this obvious anomaly is that public statistics measure productivity not by how much product a certain amount of work creates, but by the value of that product. If the product or service has, as in the examples above, become much cheaper over time then, by that measure, it is deemed to have become much less valuable. If the decline in price is large enough, this leads to the conclusion that we have lost rather than gained from these engineering advances. This does not only affect the phone itself; if you use the phone to book a cheaper taxi or consult Google rather than an encyclopaedia you have spent less money and thus have apparently lost value. When you decide to buy a new, bigger 4K TV to replace your old small one, the new one is cheaper than the old one was when you bought it. This seems like a big engineering win but, in the eyes of the official statistics, because you have spent less, it is assumed to be less valuable to you. Things would be easy if you had been offered the two TVs at the same time at their original prices, but for a rapidly advancing product this does not happen.

To help to address this anomaly in how the UK (and others) measure productivity, a team of engineers, statisticians and economists from the Institution of Engineering and Technology, the Office for National Statistics (ONS), Ofcom, and many other places, including academics and experts from the Bank of England and the Treasury, have come together to look at these statistics. The group starts from the premise that the statistics on GDP and productivity are not in themselves wrong, but they do not measure growth in wealth, quality of life or productivity as any normal person would understand these things. You are not worse off because you have a smartphone (instead of a pair of tins and a piece of string) that connects you to a world of knowledge, even if GDP says you are.

This is not just a technicality. One recent study that set out to evaluate the potential increase in GDP that will arise from 5G communications found it to be negative. Of course, no-one believes this and 5G mobile communication will roll out anyway, but following the logic of that study could lead to many other decisions going the wrong way. However, politicians and pundits still talk about the 'productivity shortfall' and the apparent lack of GDP growth without noting that much of this 'shortfall' would disappear if we measured productivity properly.

This is not fanciful. The telecom sector alone is reckoned by some to have contributed 20% to the measured UK productivity shortfall, despite its obvious opposite effect in delivering a much enhanced 'bang for the buck'. So a re-adjustment in terms of performance instead of price, just of this sector, could wipe out much of the apparent deficit.

Why does this matter to engineers? Because the numbers say that we are wasting our time in trying to do things more cost effectively and efficiently. Because, when deciding whether more skilled engineers or building infrastructure helps the economy, the apparently disappointing productivity and GDP growth performance could restrain investment. More profoundly, talk of productivity shortcomings is unnecessarily depressing about all of our futures and understates the improving experience that modern engineering has given us. It makes engineering look less 'useful' and less attractive to young people.

This issue is not new or unique to the UK: the reason it remains a concern is that it is surprisingly difficult to fix.

For many products and services, it is not easy to measure output in the way you can count loaves of bread. This is especially true where a cheap or even free modern service replaces an older one. Think for example of everyday cameras or sat navs: both are now largely replaced by functions built into smartphones. The built-in products are generally better and more convenient than the discrete devices that they replaced but at no obvious extra cost, making it hard to create a time series based on value. Although we could, in many cases, measure the gain in engineering functionality and thus 'engineering productivity' – think, for example, of the number and pixel count of pictures taken, or the number of journeys guided – without money as a unifying metric this could land us with the daunting task of doing a separate assessment of the productivity gains for each product or service.

The aforementioned group has been working initially with data on communications, the digital transport of electronic data by wireless, cable and fibre considered as a service including everything from voice to the internet. The advantage of this example is that the data is entirely digital, making it straightforward to count the quantities delivered, for example in bytes or bits, per unit cost. The communications industry is also closely regulated by Ofcom, which assembles very helpful statistics.

The results so far are promising. ONS is altering its 'deflator', which relates the price to the value, in the communications field to take account of these concerns, partially at least. The group is now moving on to consider similar issues in cloud computing services and civil engineering and construction.

The productivity conundrum is one of the most important public concerns that engineers need to address. We all need to shout about it if engineering is to be seen as the engine of our future in the way it surely is, rather than a hindrance to rising productivity. Engineers must object every time politicians and pundits talk about 'poor productivity'. We must keep telling everybody we meet: journalists, decision-makers and students of all ages, and in every report we write, that real engineering productivity is great and getting better all the time. All engineers could also help by flagging up any engineering area where you think this is a problem and where they can provide useful statistics on engineering productivity that could help dispel the myths.

Engineering matters and is the main driver of our improving lives. We need public statistics that show this, especially to and for the next generation. You are better off with a smartphone even if GDP says you aren't. It is becoming ever more important for us all to say so loudly and often, especially for the next generation.

BIOGRAPHY

Professor Will Stewart FREng is a visiting professor at the Optoelectronics Research Centre at the University of Southampton. He is a Fellow of the Royal Academy of Engineering and a member of *Ingenia*'s editorial board. He is also a Fellow and past trustee of the Institution of Engineering and Technology and chairs its Communications Policy Panel, and is a Fellow of the Institute of Physics and the Optical Society of America. His interests include photonics, communications, electromagnetics, nanophotonics, metamaterials, 3D printing and smart 999 calling.

Biofuels are liquid fuels that are derived from biomass, such as biodegradable agricultural, forestry or fishery products, wastes or residues, or biodegradable industrial or municipal waste © Shutterstock

BIOFUELS' JOURNEY TO THE MAINSTREAM

Liquid biofuels today make up about 8% of road and non-road fuel supplies in the UK. The government plans to reach nearly 10% by 2020 in order to reduce CO_2 emissions. It has also laid out targets to incentivise innovation and the production of 'development fuels'. Dominic Joyeux looked into recent growth and the focus on biofuel production for transport.

Biofuels for transport are not new. Henry Ford's first vehicles of the 1900s were constructed to run on both ethanol (distilled from hemp or potato) and petroleum. He saw ethanol as the 'fuel of the future'. However, the cheap and plentiful supply of gasoline saw fossil fuel win the battle to power motor vehicles and it was not until the oil supply crisis of the 1970s that ethanol would become a serious transport fuel contender again.

At that time, many countries showed interest in producing biofuels but only Brazil produced it in large quantities using sugar cane, which grows easily in the country. By the 1990s, when the sharp rise in crude oil prices and shortages led to concerns over energy security, the US took to producing ethanol from corn to such an extent that it now leads the world in ethanol production. The country manufactures over 60 billion litres of ethanol a year, which it blends with gasoline at a rate of 10% for the domestic market.

In the past decade, the interest in biofuels has increased again, with the development of government policies on climate change mitigation and strategies to reduce greenhouse gas emissions from the transport sector. More than 60 countries have now launched significant biofuel programmes and, consequently, biofuels now account for 4% of global transportation fuels.

In recent years, growth stalled in the UK as various controversies raged over the sustainability of biofuel production and use – for example, whether land and water used for growing biofuel feedstocks were interfering with resources for producing food. Now, with stricter definitions, better understanding and more controls over how and what feedstocks are used, the UK government is aiming to achieve the targets of the 2009 EU Renewable Energy Directive (RED): a minimum target of a 10% share of renewable energy in transport by 2020 and use of newer, non-food feedstocks.

In April 2018, the government's revised *Renewable Transport Fuel Obligation* set out aims to meet these levels. The target amount of biofuels to be added to regular pump fuel immediately rose to 7.25%, increasing to 9.75% by 2020 and 12.4% by 2032. Transport fuel suppliers that meet this sustainability criteria are awarded Renewable Transport Fuel Certificates.

WHAT IS BIOFUEL?

Biofuel is derived from biomass, biological matter that has some form of carbon in, which is passed through a chemical process to make it sufficiently energy dense to make a fuel. Unlike fossil fuels, which are produced over millions of years, biofuel is produced relatively quickly. Biofuels can be used in place of regular fuel in cars, trucks and other vehicles and, as a renewable fuel, it can offer

ENVIRONMENTAL CONSIDERATIONS OF BIOFUEL PRODUCTION

There are strict environmental criteria in place regarding what can be considered a renewable fuel and biofuels producers have developed several voluntary sustainability certification schemes for use within their supply chains. Out of these schemes, the European Commission recognises 19 that meet the requirements of the Renewable Energy Directive so can be used to certify biofuels. The ISO 13065 standard on *Sustainability Criteria for Bioenergy* provides an evaluation framework for environmental, social and economic sustainability of different bioenergy products and supply chains, which includes biofuels. It specifies a set of principles, criteria and indicators that should be used in sustainability assessments. However, the standard only deals with direct impacts – those that are "under the direct control of the economic operator and caused by the process being assessed" – meaning that indirect impacts are outside the scope of the standard.

Therefore, the relationship between biofuels and biodiversity can sometimes be complex. Biofuel production can potentially threaten local biodiversity through areas such as habitat loss and degradation, intensive cultivation, excessive use of agricultural chemicals and other forms of pollution, overexploitation and unsustainable use of land. The impact of their production on biodiversity depends on the feedstock used and scale of production, management practices and land-use change (when human activities transform the natural environment).

The reduction of greenhouse gas emissions is the main environmental driver for the use of biofuels. Lifecycle assessment of feedstocks used for bioenergy is a way to measure their carbon footprints in comparison to those of fossil fuels. Studies have found that while biofuels are cleaner to burn, the process to produce the fuel, especially with first-generation crops, can have hefty carbon emissions. For example, if the market demand for biofuels drives land-use change, such as deforestation of tropical rainforest, the carbon footprint of bioethanol from sugar cane can be much higher than that of petrol.

Water use is another important consideration when trying to evaluate the environmental effects of producing biofuels. Some biofuel crops require large amounts of water to irrigate them. Similarly, manufacturers sometimes need large amounts of water, even if second generation (produced from waste) feedstocks are being used. This can put a strain on local and regional water resources.

For so-called first-generation feedstocks (food crops), the effect on food prices is another consideration. As the demand for food crops, such as corn, grows for biofuel production then prices for staple food crops could rise, leading to food shortages.

significant environmental benefits including reducing emissions of greenhouse gases.

Almost any biological material could be turned into some sort of fuel with varying degrees of manufacturing efficiency and energy input/output. The science says that it is possible, but it is the economics behind the process and the ethics, such as whether there is an alternative need for the feedstock, that influences policymakers and determines take-up.

However, major barriers to the wider adoption of biofuel are the production costs and the impact of diverting food resources to fuel use. It is therefore increasingly important to produce biofuels from alternative oil sources unsuitable for human consumption and there are many sources of low cost waste oils: from restaurant waste to rendered animal fats. It is estimated that one million tonnes per year of waste oils are collected in Europe alone. Disposing of these waste oils can be hugely problematic as they can contaminate water in the environment, but one excellent way of disposing of them is in biofuel production.

TYPES OF BIOFUEL

The two main types of liquid biofuel used for road transport in the UK are bioethanol, which accounted for 49% of renewable fuel, and biodiesel, which made up 47% of the total 1,540 million litres produced in 2016/17. Fuels produced from food-crop feedstocks are classified as 'first generation' biofuels. Those that replace food-crop feedstocks with feedstocks from various waste sources, thereby avoiding competition with food, are classified as second generation; for example, to qualify as a second-generation feedstock, the source must not be suitable for human or animal consumption [see *Liquid biofuels classification*].

First-generation bioethanol is a biofuel produced through the fermentation of carbohydrate or sugar crops such as wheat, sugar cane and sugar beet. Second-generation bioethanol is being produced in the US from cellulosic biomass or crop residues. It has about two-thirds of the energy per mass of petroleum, which means that when there is 10% ethanol/petrol blend it will have 97% as much energy as petrol. Ethanol burns cleaner than petrol and so produces less carbon (soot) and carbon monoxide.

Biodiesel is made through the esterification of fats, a chemical reaction in which two reactants, typically an alcohol and an acid, form a chemical compound. The common first-generation feedstocks for this include edible oils such as rapeseed and soybean oil, while second-generation fuels are being produced from waste products such as used cooking oil and tallow. Biodiesel is only slightly less energy dense than regular diesel and burns cleaner, producing fewer particulates and sulphur compounds, so extending the life of catalytic converters.

In order to incentivise their use over first-generation biofuels, some EU member states 'double count' second-generation biofuels towards obligations to blend low-carbon fuels into the fuel pool. Double-counted biofuels are issued double the number of Renewable Transport Fuel Certificates. For example, in the UK, short rotation coppice

LIQUID BIOFUELS CLASSIFICATION

Classification	Alternative classification	Feedstocks	Production	Products
First generation	Conventional biofuels	Sugar crops Starch crops Vegetable oils	Transesterification Fermentation	Bioethanol Biodiesel
Second generation	Waste-based biofuels*	Used cooking oil Animal fats Energy crops	Hydrogenation Fischer-Tropsch Gasification Pyrolysis	Biomethanol Biobutanol Biopropanol Bioethanol
	Advanced biofuels	Agricultural residues Forest residues Sawmill residues Wood wastes Municipal solid waste	Hydrolysis	Mixed alcohols Jet fuels Hydro-treated vegetable oil
Third generation		***Development stage*** Algae and others		

**Used cooking oils and animal fats are converted via well-established processes. Some energy crops compete with food or feed crops or cause land-use change; hence they may not qualify as feedstocks for second-generation (advanced) biofuels (adapted from International Renewable Energy Agency (IRENA) publication)* is grown as double-counted feedstock for biodiesel.

The Royal Academy of Engineering's 2017 report, *Sustainability of liquid biofuels*, made strong recommendations that incentives should be given to farmers to increase production of energy crops such as miscanthus on marginal land. It also pointed to the 16 million tonnes of waste that could be used for biofuels every year – a third being green waste and a quarter agricultural straw. It also highlighted the use of unavoidable waste such as cooking oil, forest and sawmill residues, and fatbergs from sewers.

E10 is a biofuel made up of 10% bioethanol and 90% regular unleaded, said to reduce greenhouse gas emissions. It is currently sold across Germany, France and Finland, and the UK government is considering rolling it out across the UK. However, many cars are unable to use the biofuel and research by *What Car?* has showed that it is potentially less efficient, meaning drivers would have to fill up their engines more regularly

CONVERTING WASTE OILS TO BIODIESEL

Converting waste oils into biodiesel is a useful method of tackling the problem of their disposal. However, conventional biodiesel processes can struggle to convert them because of the high fatty acid contents. Fatty acids are a carboxylic acid consisting of a hydrocarbon chain, which is either saturated or unsaturated.

Aiming to address this problem, Johnson Matthey (JM) developed a reactive distillation process for fuel-grade biodiesel production using used cooking oil as a feedstock. This involved employing a reactive distillation column developed by JM's chemical engineers and chemists. This distillation column is used to separate components according to their boiling point differences, but reactions also occur, which adds to the design's complexity.

However, creating this technology had many technical challenges. The first challenge was developing a technology that could process waste oils of varying composition and impurities. To tackle this, the plant design needed flexibility to allow for the variability and quality of the feedstocks. JM's research and development site in Stockton-on-Tees was used to test a range of feedstocks to ensure that the materials were compatible with its equipment design and proprietary catalyst. The end goal was to guarantee that the required conversion and feedstock efficiency could be delivered.

Further technical challenges were achieving low organic content in the wastewater effluent stream and efficiently separating methanol from the product. JM developed proprietary processes to address these while minimising plant and utility costs. To ensure that the lowest overall costs are achieved, chemical engineering always aims to add value through chemical transformation, or monetising the chemicals, while using the least amount of equipment and utilities.

Unlike traditional process routes that rely on converting triglycerides (a compound formed from glycerol and fatty acids), JM's process uses fatty acids, typically a major constituent of waste oils. Because the process does not divert vegetable oils away from food production, it does not place additional demand on edible oils for non-edible uses, offering a more sustainable way of dealing with material that would otherwise be lost as waste.

JM's innovative process transforms a waste that is usually hard to dispose of into a sustainable clean product. The technology was also later recognised at the annual Institution of Chemical Engineers' Awards.

AIR AND SEA

The government's *Renewable Transport Fuel Obligation* established percentage targets for the use of biofuels within regular fuel at the pump, as well as setting up new 'sub-targets' that encourage innovation of 'development fuels' and investment in the aviation sector.

The target for development fuels will rise from 0.1% in 2019 to 2.8% in 2032, equating to production levels of 500 million litres per annum by 2030. Today, there are 30 gas-filling stations in the UK and two dedicated to solely dispensing biomethane (from food waste) in Leyland and Crewe.

The new law introduces hydrogen, of non-biological origin, as a renewable fuel, so water being electrolysed would count. It also mentions gasification, producing a mix of carbon monoxide and hydrogen, from which methane can be made. That gets an extra incentive as it is defined as a development fuel, rather than producing the same result through anaerobic digestion (a series of biological processes in which microorganisms break down biodegradable material without oxygen present), which no longer gets incentivised through certification.

The government has targeted the aviation sector because it is the second largest consumer of energy in the transport industry. It also accounts for at least 2% of worldwide CO_2 emissions. Internationally, the aviation industry has set ambitious goals for reducing its emissions, aiming for no net increase from 2020 onwards and a 50% reduction by 2050 compared to 2005.

Until recently, the major hurdle had been the difficulty of producing high purity, chemically stable renewable fuel that did not freeze at 30,000 feet. Aviation fuel has special requirements, including a need for high energy density, and biofuels such as biomethanol and bioethanol have relatively low energy densities – aeroplanes using such fuel would have a limited range or would need to carry an enormous amount of fuel.

Aviation fuel serves as more than just combustion in an aircraft; it also functions as a lubricant, cooling fluid and hydraulic fluid. Fuel producers have used and trialled various feedstocks including municipal solid waste, cellulosic waste, used cooking oil, crops such as camelina (false flax) and jatropha (a semi-evergeen shrub also known as physic nut), and even waste gases from industrial processes such as steel manufacture.

In 2008, Virgin Atlantic successfully flight tested a Boeing 747 using a 20% biofuel mix, derived from babassu palm oil and coconut. Since then, thousands of commercial flights have operated using biofuel that is blended with Jet A fuel in the US and Jet A-1 fuel, which is based on unleaded kerosene, elsewhere. 'Drop-in' fuel – a synthetic fuel substitute – has similar qualities to standard jet fuel, which means that engines, fuel systems and fuel distribution networks do not need to be adapted.

A Lufthansa aircraft is refuelled at Oslo airport © Tom Parsons

FROM FATBERG TO FUEL

Argent Energy is a big player in processing used oil for biofuels and has gained a reputation for developing innovative ways to exploit difficult-to-convert waste such as old soup stock and stale mayonnaise. The company's two large plants in Motherwell and Stanlow have a capacity to produce 145 million litres of biodiesel a year. In 2005, Argent pioneered the use of tallow – rendered mutton, beef or other bovine fat – for commercial scale biodiesel production. Its patented pre-treatment process both filters and sterilises the tallow so that it can be used as a raw material for biodiesel.

Argent then started to 'harvest' sewage sludge taken from the water-treatment process. It solved the challenge of converting low-grade sewer fat into a useable fuel. This waste now constitutes 10% of the company's biodiesel manufacturing. In 2017, the company hit the headlines when it invited Thames Water to send it some of the 250-metre long, 130 tonne Whitechapel fatberg. The company's chemical engineers worked on the fatberg at a pre-treatment plant at Ellesmere Port and converted 30% to 40% of what was sent through to biodiesel feedstock.

A small section of the infamous Whitechapel fatberg while it was still in the London sewer system © Thames Water

Since its first commercial use, the technological progress of aviation biofuel has been substantial, although take-up has been relatively modest. In November 2017, a milestone was reached with 100,000 commercial flights undertaken using fuel blended with biofuel. One of the biggest obstacles is the economies of scale that need to be achieved, entailing scaled-up refining and processing capacity. To help make this happen, the low carbon transportation fuels company Fulcrum BioEnergy is building a waste-to-jet biofuel plant in the US [see *Using Fischer-Tropsch to convert waste*].

The marine sector is another important user of fossil fuel, consuming over 330 million tonnes every year and contributing to an estimated 2% to 3% of global CO_2 emissions. Compared to road transport and aviation, shipping uses much less refined fuel types. Marine fuels are primarily produced from crude oil and mainly use heavy fuel oil and marine diesel oil. Emission control areas on North American and European coastlines enforce strict limits on sulphur oxides and nitrogen dioxide, which means that low-polluting fuel alternatives have been developed. Now there is a focus on biofuels that will work in the marine sector too.

Although there is no mention of marine fuels in the *Renewable Transport Fuel Obligation*, the industry itself has looked at possible biofuel take-up. Currently, the higher price of biofuels and the lack of sufficient logistical support at ports for fuels that are not compatible with diesel-type fuels are proving obstacles to implementation. It may be that other alternatives to liquid fuels such as hydrogen, electric and natural gas will be the preferred option for reducing greenhouse gases for ship owners worldwide.

THE ROAD AHEAD

The future take-up of biofuels in the UK depends on many variables. It could be that sales of electric cars will cut the need for biofuels, that hydrogen for trains becomes a viable possibility or that biogas for lorries will be the favoured option. The pathways to decarbonisation are many and varied with unknown factors still able to trip up the best-meaning policymaking intentions.
In terms of government direction, there is now a focus

USING FISCHER-TROPSCH TO CONVERT WASTE

Developed in 1925, the Fischer-Tropsch (FT) process involves a series of chemical reactions that convert a mixture of carbon monoxide gas and hydrogen gas (known as synthetic gas or syngas) into long chain hydrocarbons. In 1996, Johnson Matthey (JM) first began collaborating with BP to develop a technology that used the FT process to create diesel or jet fuels from renewable feedstocks.

To demonstrate the potential of the FT process for creating synthetic fuels, JM and BP built the Nikiski Demonstration plant in Alaska, the largest FT facility ever built in the US. The plant, which was decommissioned in 2009, featured the first generation of FT-processing technologies. It combined three core processing steps: syngas generation by novel compact steam reforming of natural gas; a cobalt-catalysed, fixed-bed tubular reactor to convert the syngas into the hydrocarbon chains; and mild hydrocracking facilities that produce synthetic crude fuels. At its peak, the Nikiski plant could produce 300 barrels of synthetic crude product per day.

JM and BP's collaboration continued to make significant improvements to the reactor system, including the recent development of the catalyst carrier technology. The new reactor uses smaller cobalt particles to improve productivity and selectivity. The catalyst carrier reactor was redesigned to be more compact, reducing the number of tubes required by around 95% and total capital expenditure by 50% when compared to conventional tubular technology.

This close collaboration makes FT applications possible at both small and large scales, with the capability to produce as much as 6,000 barrels per day from a single reactor. The success of the catalyst carrier technology relied on the combined expertise of both JM and BP. The BP team improved the catalyst particles by optimising their chemical and physical properties for the conditions of the carrier, while the JM team leveraged expertise in engineering science to improve the reactor concept. Their joint design has been validated by over 16,000 hours of operations at JM's research and development facility in Stockton-on-Tees.

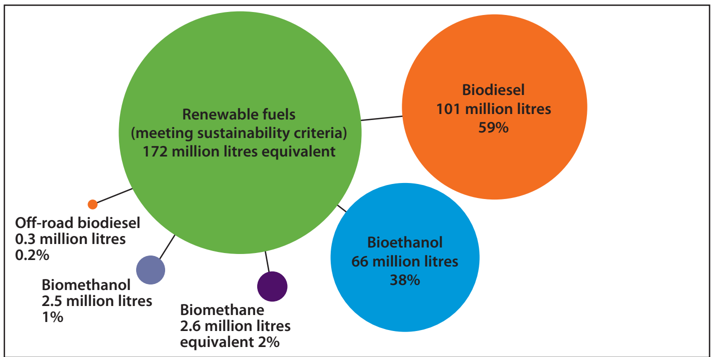
Fulcrum BioEnergy is now using this technology at its biofuels plant, located outside of Reno, Nevada. It will be the first US plant to produce a renewable fuel from municipal solid waste or household rubbish, first sorting the waste to recover recyclables and remove material not suitable for processing, before gasifying the waste to produce a syngas. Several of JM's other catalysts and absorbents will then be used to help purify the syngas before it passes to the FT reactor to produce synthetic fuels.

When the plant begins operation in early 2020, Fulcrum BioEnergy is expected to convert approximately 175,000 tonnes of household waste into approximately 11 million gallons of fuel each year: equivalent to the fuel that is needed for more than 180 return flights between London and New York.

on ensuring that the UK's energy mix is environmentally and economically sustainable. Feedstock supply chains are now being scrutinised and certified for their sustainability credentials and bioethanol has reached similar price levels to fossil fuel. Renewable diesel is more expensive than its fossil equivalent but because it is blended at only 7% with standard diesel, the price difference for the consumer is small.

The coming decades will see further innovations in biofuel development. A possible win-win result would be an increase in the nation's fuel security while at the same time reduced waste to landfill and lowered greenhouse gas emissions.

BIOFUELS IN THE UK



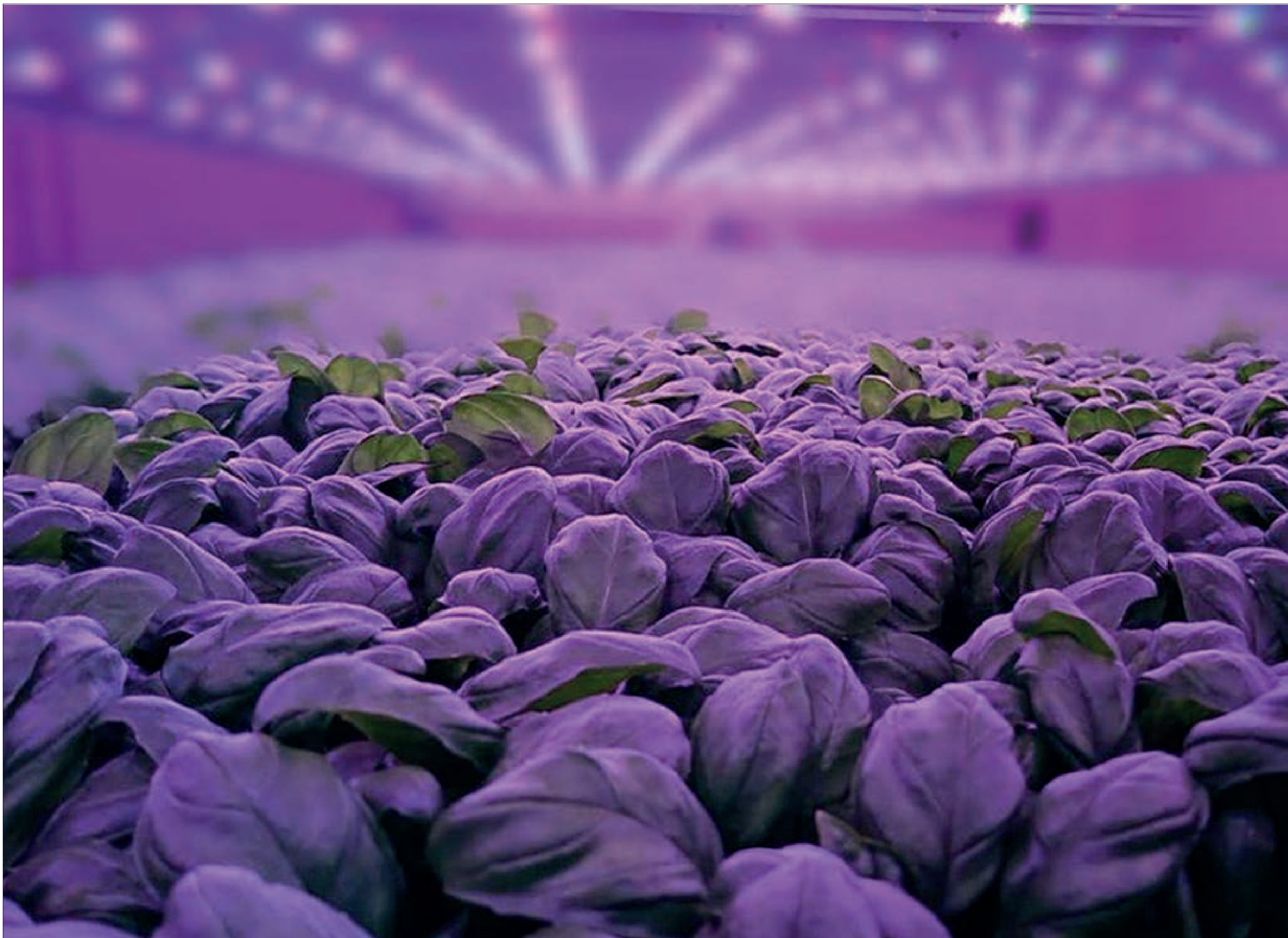
Volume of renewable fuels used in the UK between 15 April 2018 and 31 December 2018

- Liquid biofuels account for 4% of total road and non-road mobile machinery fuel (equivalent to 525 million litres).
- 172 million litres of this fuel met sustainability requirements – the government has awarded 320 million Renewable Transport Fuel Certificates to transport fuel suppliers that have met these specifications.
- 86% of the fuels that met the criteria were made from a waste or residue feedstock (second generation).
- UK feedstock accounted for 26% of the biofuel.
- The most widely reported source for biodiesel (by feedstock and country of origin) was used cooking oil from the UK.
- The most widely reported source for bioethanol (by feedstock and country of origin) was starch slurry (low grade) from France.
- Renewable fuels achieved an aggregate greenhouse gas saving of 83%, compared to fossil fuels in this period.

All figures were taken from the Department for Transport's Renewable Transport Fuel Obligation statistics: period 11 (2018), report 1, *which covered the period from 15 April 2018 to 31 December 2018.*

The author would like to thank contributors to this article who include: Gaynor Hartnell, Head of Transport Fuels and Landfill Gas, Renewable Energy Association; Dr Andrew Chilvers, Senior Policy Advisor, Royal Academy of Engineering; Tom Parsons, Commercial Development Manager – Biojet, Air BP ; and Andrew Coe, Technology Manager – Fischer-Tropsch, and Michael Winter, Technology Manager, both from Johnson Matthey.

To read the report, Sustainability of liquid biofuels, *please visit* ***www.raeng.org.uk/biofuels***



Indoor farming, especially in vertical farms, is creating optimum conditions for many types of crops to grow, potentially increasing savings and reducing space needed
© Intelligent Growth Solutions

FARMING FOR FUTURE GROWTH

Agriculture faces mounting challenges in the 21st century. More of us live in cities than ever before and the global population is estimated to reach 11.2 billion by 2100. Science writer Sarah Griffiths spoke to Intelligent Growth Solutions' Niall Skinner, Senior Mechanical Engineer, and Douglas Elder, Product Manager, to understand how produce grown inside under lights in trays arranged in vertically stacked towers could help meet growing demand for food.

Current farming methods are often wasteful in terms of space, water and money. However, vertical farms, which grow crops in trays stacked in tall towers, could help to reduce food waste by up to 90%. They would help to grow produce locally and on demand, and the growing process could allow farmers to control the environment whatever the season, changing the intensity and length of exposure to light, temperature, humidity, water irrigation, nutrients and carbon dioxide levels to create optimum conditions in which crops can thrive. In the future, these vertical towers could replace greenhouses at about half the cost, and with increases in savings and a reduction in space used.

This agricultural revolution is not a new concept; in 1909, *Life* magazine published one of the earliest drawings of a vertical farm. In the 1950s and 60s, prototypes were first produced. In 1999, the idea was reintroduced by Dickson Despommier, a professor of environmental health sciences and microbiology at Columbia University, who speculated that a 30-floor farm could provide food for 50,000 city-dwellers. While many of his ideas have been challenged, vertical farms are now a reality in the US, Europe and Asia, where they are popular in cities where space is at a premium. In 2016, there were 2.3 million square feet of indoor farms across the globe, and this is expected to grow to between 8.5 million square feet and 16.55 million square feet by 2021. However, the UK's vertical farm industry has previously been described as 'underdeveloped' as only a few crops, including lettuces, are grown in a few operational vertical farms. But the UK does have Europe's largest vertical farm owned by Jones Food Company, which is 17 storeys high.

Scotland's first vertical farm, operated by Intelligent Growth Solutions (IGS) at the James Hutton Institute in Dundee, uses new technologies to overcome challenges presented by power and labour costs, which have inhibited the sector's expansion so far. IGS claims its growth tower is the most advanced vertical farm design developed to date because it allows experts to monitor and control growing conditions, learning from mistakes and improving the environment using artificial intelligence (AI). A key breakthrough for the system has been in the way that it manages power consumption, particularly through the development of LED lighting, which has reduced energy costs dramatically. The demonstration facility opened in August 2018 and the company expects 95% of its technology to be exported, with the first installations already being deployed in the US.

The current farm has space for four growth towers, each with a growing area of approximately 310 square metres, but only occupies a footprint of 41 square metres. The towers are individually housed in a standard steel frame warehouse building with insulated cladding walls to provide isolation from the external environment. Each tower, which is currently growing a range of fast-growing herb and leaf crops, has standalone ventilation and irrigation closed-loop systems that automatically sterilise and recycle air and water so that the only regular inputs that the system needs are power, seed, nutrients, carbon dioxide and harvested rainwater. Within each tower, all important parameters – light, heat, humidity, water, nutrients, and crop movement – are controlled by industrial programmable logic controllers (PLCs), which are computers that run on an architecture that does not need unpredictable updates. The Omron SYSMAC PLCs use feedback from sensors distributed throughout the tower and systems that is transferred to a cloud-based control system

The Dundee farm is housed in a purpose-built superstructure that has insulated cladding to protect crops from the external environment. The structure has space for four growth towers © Intelligent Growth Solutions

THE BENEFITS OF VERTICAL FARMING

- Good for the UK: the UK's population is growing at about 0.6% a year and the country is expected to face a shortfall of two million hectares of farmable land by 2030, making vertical farms a practical, space-saving solution.
- Crops are grown locally: this produces near-to the demand for food, so reduces food miles, cutting costs. Salad crops and ground fruit would be grown in vertical farms in the short term. The method of farming also increases food security, by reducing dependency on imports.
- Food is better quality: proponents of vertical farming say the method improves the appearance of food, as well as its nutritional qualities and taste, which remain consistent year round because of growing conditions. Crops are disease-free, eliminating the need for pesticides, while semi-hydroponic techniques eliminate the need for washing, reducing contamination.
- Natural resources are saved: vertical farms have a much smaller footprint than fields, freeing up farmland for alternative use, such as energy crops or for conservation. Furthermore, the ability to recycle water reduces its consumption by 90% compared to field growing and makes it around 10% more water efficient than greenhouse growing.
- Saving money: the reducing cost and improving electrical efficiency of LEDs, compression of the value chain, production matched to consumer demand, reducing wastage and integrated automation reduced labour costs mean vertical farming can cut costs.

in real time, allowing experts to constantly monitor and adjust the growth environment to optimise production. This system uses AI algorithms that analyse the growth results, learn from production and calculate the best way to boost output by suggesting tweaks to the growing environment. The idea is that a commercial farm could be controlled via an app and the system managed by engineers instead of farmers having to get to grips with extra cables and computers.

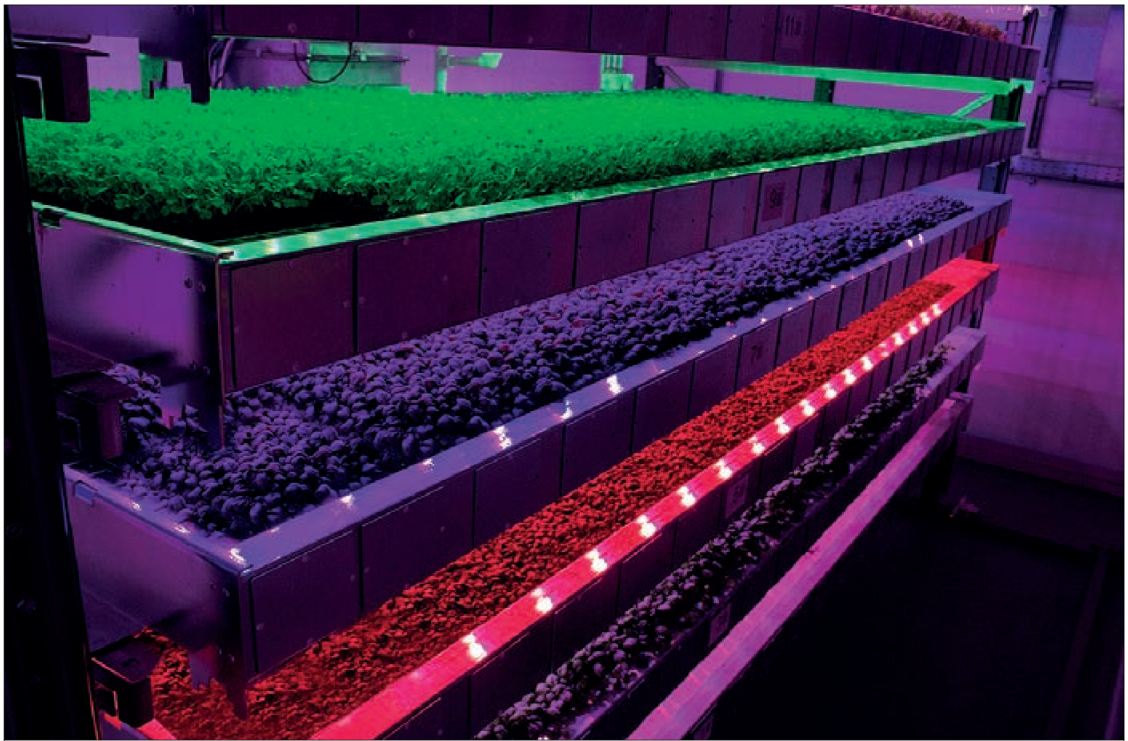
MANAGING POWER CONSUMPTION

To overcome the challenge of energy consumption, IGS designed a power-management system that flexes with the grid in real time, so that it responds to external influences such as grid stability and power availability, importing power when cheap or exporting it when costly. This means that the facility effectively acts similarly to a large battery where the energy is converted into food. The use of industrial Omron SYSMAC PLCs within the facility allows automatic recovery from power loss events and means that individual towers and sites get the power they need, meaning that none of the systems need to be reset, reprogrammed or manually repositioned. Each tower has a baseline power consumption of 60 kilowatts (kW), which can be rapidly increased to 105 kW or reduced to 30 kW for short periods to optimise grid stability, while the impact on growing is managed by the control system's AI elements.

Heating and air conditioning can be a drain on power resources. However, the watering, heating, ventilation and air conditioning systems are also closed loop, which minimises their impact. The design also reduces the need for

HEPA (high efficiency particulate air) filtration to clean large volumes of incoming air, and the potential heating and/or cooling of this air depending on location and season. The air is sterilised by UV filtration technology, similar to clean rooms, and heated by the waste heat from LEDs that are used to mimic the sun. Standard industrial chillers and cooling coils cool and dehumidify the air, before it is passed back over the LEDs for preheating and then returned to the crop. Carbon dioxide can be added to this loop when required too.

Lighting uses approximately 70% of the system's power, which is not surprising as there are 1,140 LEDs per tray. To improve the efficiency of power transmission to the lights, IGS developed a power distribution system for driving the LEDs, which takes an industrial three-phase power supply, transforms it to a safe voltage level and transmits it to each individual tray within the tower using tubes rather than cables. The use of tubes rather than cables improves transmission efficiency because of the skin effect in cables. When electrical AC power is transmitted through a cable, magnetic effects cause the current to be forced to the outside 'skin' of the conductor. This reduces the useful cross-sectional area of the cable. The presence of conductive material in the centre of the cable gives rise to these magnetic effects, so the use of tube rather than cable actually reduces the cause of skin effect, allowing better distribution of current through the remaining conductor material and improving transmission efficiency. This effect is driven by the AC frequency and conductor diameter, with a 9 millimetre cable diameter being the key threshold parameter for efficiency with 50 hertz supplies. Due to the safe low voltage used to transmit power to the trays the current and cable diameter is large, leading to significant advantage in the use of tubes over cables. A side effect of this is that aluminium tubes are also much cheaper and lighter than suitable copper cables. The retention of three-phase AC power to a tray level further reduces losses and provides inherent phase balancing, eliminating the need for costly and inefficient filtering and power factor correction, as well as the use of capacitors for single phase conversion. These measures contribute to a 5% to 10% increase in driver efficiency.



Different coloured LEDs are used to nurture the plants at different stages of growth, with the intensity increasing and dimming when needed © Intelligent Growth Solutions

LIGHTING UP THE FARM

Many indoor growing facilities use red and blue lights to nurture plants, after scientists demonstrated that not all wavelengths of light contained in sunlight are needed for effective growth. More recent research has shown that varying the spectrum used at different stages of growth can also offer a significant improvement in the crop yield. This system uses four different wavelengths of red, blue and green LEDs and has experimented with others including far red and white. The LEDs are fitted in clusters, with each cluster containing all types of LED. The team then varies the light intensity and/or dimming for each individual colour to control the spectrum. This dimming is controlled by its LED driver boards, which are wirelessly connected to the PLC controller. The ability to vary the spectrum used has been a key focus for IGS and the company says that the ability to control the spectrum or pulse width modulation (PWM) and intensity to simulate solar radiation is unique among vertical farms. Each wavelength can be turned on or off or dimmed via PWM, linear dimming or a combination of both. However, while the facility has this ability, the precise optimal mix of light for each crop and stage of growth is not well understood, so the team is using AI to measure and understand the crops' progress, in order to accelerate learning in this area. Its observations within a controlled environment are challenging some of the current thinking in terms of important wavelengths and data will be used at the farm to further boost plant production.

For example, while research has shown that green light does not directly contribute to photosynthesis to any great degree, IGS has shown that adding green light, particularly at certain stages of growth, increases both crop yield and quality. Its scientists believe the green light is acting as a trigger

The challenge is not allowing the plants to grow excessively tall and leggy, so using AI to learn the effects of far red light at different stages of growth allows IGS to produce crops suitable for market with the minimum energy input, by only using far red light where it has most effect

to improve photosynthetic processes, rather than the dominant effect being a contribution to photosynthesis. Similarly, the company uses far red light because it stimulates stem growth, rather than directly contributing to photosynthesis. This means that doses of far red light at certain phases of growth can be used to alter the plant's shape or structure by promoting stem growth in a controlled manner. The challenge is not allowing the plants to grow excessively tall and leggy, so using AI to learn the effects of far red light at different stages of growth allows IGS to produce crops suitable for market with the minimum energy input, by only using far red light where it has most effect.

Alongside the spectrum of light used, the method of how it is delivered to crops could affect how well they grow, and the facility can vary both intensity, through linear dimming or PWM, and PWM infinitely in 0.01% increments over all wavelengths simultaneously and maintain 90% electrical efficiency from grid to LEDs. As biological systems, plants have response times to stimuli in the same way as we do. One such response is the time taken to activate photoreceptors within the plant to perform photosynthesis, as well as the time to shut down again once it has gone dark. This means that plants are not as efficient as they could be in performing photosynthesis and that a pulsing light regime could be used with a pulse duration long enough to keep the plant photosynthetically active. Not only would this boost the plants' efficiency at converting water, carbon dioxide and light energy into glucose and oxygen, but it could mean that less light is needed overall for the same growth result, potentially benefiting the farmer and saving money. Currently, this is not a proven field and scientists are not sure what the mechanism is that manages the photosynthesis response, but IGS's initial work shows that similar yields can be produced by pulsing the same intensity of light as when it is on continuously, which means the crop is producing the same yield for less light photon input. IGS has reported promising initial results with the system and it is a further reason for the AI control to enable optimisation.

MONEY MATTERS

The UK's agri-food supply chain accounts for an annual turnover of £96 billion with revenues of £10 billion, accounting for 6.4% of the UK's gross value added according to a Defra report published in 2018. The agri-tech industry, supporting farmers and growers with machinery and other kinds of technology, is a multibillion pound sector in which the UK has a 4% to 5% share of the world market. Vertical farming technology could potentially make the UK a leader in this area.

Farmers worldwide face a common set of challenges: population growth, dwindling land, water and energy resources, climate change, and the need to increase efficiency and lower costs. It is hoped that vertical farming will play an important role in tackling these problems. Niall Skinner, Senior Mechanical Engineer at IGS, said that economic benefits include improved yield and reduced wastage for each crop produced. For example, a typical glass house growing basil produces about 30 kilograms per square metre a year, but the vertical farm produces almost double. The technology allows a year-round growing season, which could mean eating strawberries in winter is less environmentally damaging than flying them in from abroad. However, it is difficult to calculate energy and carbon savings, because there are so many factors that determine the cost of production. Douglas Elder, Product Manager at IGS, said the cost of power is the biggest factor because it is determined by scale, location and power generation technique. However, the company produces two to three times the amount of greenhouse-grown crops that require supplemental lighting heating and cooling, putting its production costs per kilogram in the same range.

It is anticipated that vertical farms would be built near cities and/or distribution hubs, so there would be fewer transport costs and a reliable supply because farmers would be less dependent on the weather, potentially saving large amounts of money by avoiding crops spoiled by drought or frost. While the amount farmers save on buying pesticides is unlikely to cover the cost of power for lighting, it will help. Elder said that critics should also consider a massive reduction in wastage through improved regularity of supply and predictability for the retailer, meaning fewer losses. Smart vertical farms could also cut farmers' utility bills, thanks to the ability to minimise power

Vertical farms are ideal for crops that are usually grown in greenhouses, such as salad vegetables, herbs and strawberries © Intelligent Growth Solutions

costs through grid balancing or flexing (especially at larger scale) and use water more sparingly and effectively. Farmers could also save money when buying or renting land because vertical farms have a much smaller footprint.

However, much like other agri-tech equipment, a vertical farm would be a huge investment. One way to overcome this might be to rent them, much as farmers tend to lease tractors and combine harvesters. IGS has not ruled this out and says its software and support services will be offered on a subscription basis to allow customers to access the latest developments. However, it envisages farmers spending on a vertical farm upfront could recoup their investment in two to four years, thanks to better efficiency and higher crop yields. IGS says this estimate is dependent on a grower's ability to successfully establish the necessary supply chain.

However, if the investment was readily available, farmers could grow their vertical farms as the system is designed to be scaled, with all elements being modular to allow additions at any time. The towers and control system are fully automatic, and the design allows for as much or little automation outside of this as desired by the farmer or local economics. It is anticipated that most commercial facilities consist of 20 growth towers or more, but vertical farms could be as small as two towers. The growth trays are all returned to the base of the towers for planting, watering, fertigation, harvesting and monitoring, which is designed to work with existing automated harvesting equipment or can simply be removed by hand. Its system has also been designed to self-monitor and provide predictive maintenance capabilities to cut both maintenance costs and labour, providing work schedules for maintenance staff to verify that tasks have been completed. The systems engineering approach adopted in design means that there is a large degree of spares commonality and so the spares inventory for even a large facility can be small.

THE FUTURE IS VERTICAL

While vertical faming is not expected to replace conventional farming, it is expected to form part of the solution for feeding growing cities and meeting the challenge of food security. We could be eating more fruit and veg grown in indoor farms here in the UK, as IGS aims to have the first commercial farms in operation by late 2019. According to Skinner, the technology will focus more on market expansion than replacing traditional farms, partly because not all crops can be grown in an indoor environment. While arable crops are not suited to these systems because they need broad acre production to reach the volumes required, vertical farms are perfect for produce such as salad vegetables and ground-fruit crops such as strawberries. Elder states that the company's controllable lighting technology may also be suited to growing exotic crops such as vanilla, but this has yet to be tested. Whatever the case, vertical farms will probably replace glasshouses and polytunnels, seizing around 30% of the market, so it may soon become the norm to buy fruit and vegetables grown in vertical farms.

BIOGRAPHY

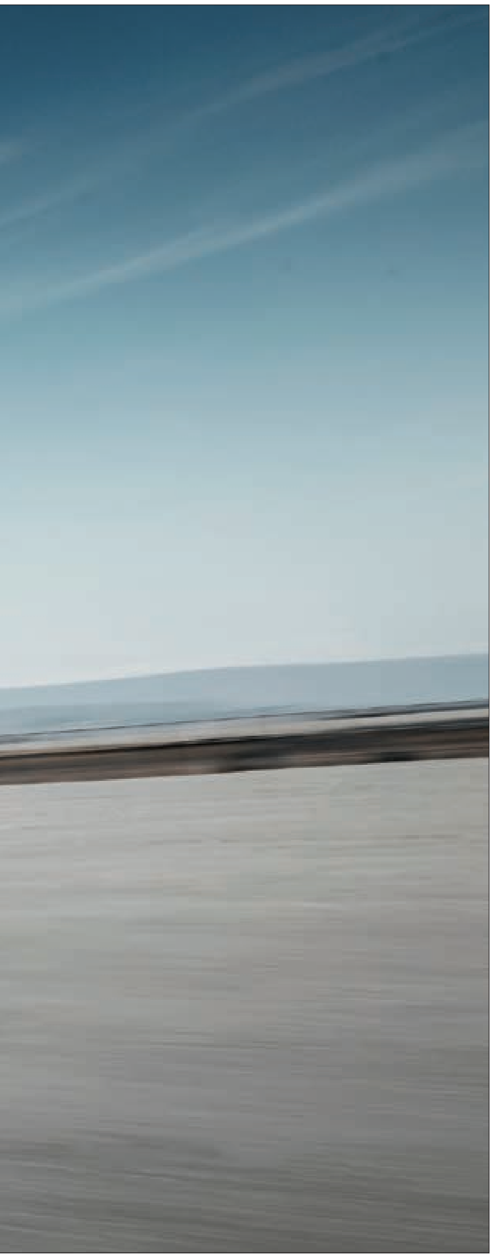
Niall Skinner is Senior Mechanical Engineer at Intelligent Growth Solutions, where he has been integral to mechanical and ventilation design. He has over 20 years' engineering experience. Niall studied product design engineering at the University of Strathclyde, and during his time there received a Royal Academy of Engineering leadership award.

Douglas Elder is Intelligent Growth Solutions' Product Manager, responsible for overseeing all product development from idea to launch. He has a master's degree in mining geology and began his career as a geologist in onshore oil and gas, focusing on unconventional resources in the UK and Poland for seven years. He was part of the team that achieved the first commercial unconventional gas flowrate in Europe.

THE RIGHT CLIMATE FOR EFFICIENT SEMICONDUCTORS

Silicon carbide, a semiconductor material that helps to reduce wasted energy in electrical circuits, is being used to increase efficiency in many power systems. One such application is in the electrical system of the all-electric Model 3 Tesla © Timothy Artman/Tesla

Electrical energy is wasted in countless electrical circuits that increase or decrease voltages, and switch between AC and DC. A new generation of devices made from silicon carbide and gallium nitride, semiconductor materials with wider bandgaps, is reducing these losses and decreasing the carbon footprint of many electrical and electronic devices. Richard Stevenson, editor of *Compound Semiconductor* magazine, explores how these materials have developed.



Average global temperatures are rising, with the worst-case scenario having devastating implications. Humans are encouraged to make changes to their lifestyles to try to curb the heating of our planet. Some options are not going to be universally popular, as many of us enjoy tucking into a steak, holidaying on different continents, and taking the car rather than the bus.

However, there is one change that could be easier to implement and be done without the average person even knowing: moving to greater efficiencies for the conversion of electricity every time it changes from one form to another. For example, converting between alternating and direct currents (AC and DC), changing the voltage or frequency, or a combination of these. Power conversion is inherent in the electrical systems of many products, from high-speed bullet trains and electric cars to laboratory equipment and solar panels, but energy is often wasted during the process.

The simplest way to increase efficiency and reduce losses during electricity conversion is to improve the prevailing technology: silicon power devices. However, these devices have been refined over many years, and it would take significant effort and scientific breakthroughs to deliver even a modest gain to the efficiency of the key components: the diodes, which block current in one direction, while allowing it to pass in the other; and the transistors, the switches that turn the current off and on.

A far more promising approach is to develop diodes and transistors from semiconductor materials with superior attributes, such as silicon carbide (SiC), gallium nitride (GaN) and gallium oxide (Ga_2O_3). The gains in efficiency are so significant that leading silicon device manufacturers have been investing in alternatives for several years. While sales of silicon still dwarf the alternatives, shipments of devices made from SiC are well established and rising rapidly. According to French market analyst Yole Développement, revenue for SiC power electronics hit $460 million in 2018 and will rocket to $1.5 billion by 2023.

The advantages that SiC has over silicon stem from the far higher value of its bandgap. Excellent electrical conductors, such as metals, have a bandgap that is zero, while insulators, which do not conduct, have an incredibly high bandgap. In general, the wider the bandgap, the more efficient the power conversion.

Thanks to its higher bandgap, a SiC device that is as thick as one made of silicon can block a far higher voltage. Alternatively, a far thinner device can block the same voltage, while reducing the distance that current must flow. This cuts resistance, creating more efficient devices with lower losses.

Another merit of SiC devices is that they can turn on and off more quickly than those made from silicon, so waste less energy when switching. This strength is highly valued in modern electrical circuits used to either convert signals between AC and DC forms, or step up or down voltages, as this is often carried out by switching currents on and off at frequencies of tens of kilohertz or more.

The significant energy savings associated with the more abrupt switching of SiC, allied to its lower resistance, are highlighted in comparisons of circuits equipped with these devices and those sporting only silicon electronics. For example, measurements by the Fraunhofer Institute for Solar Energy Systems show that replacing a silicon transistor with one made with SiC propels the efficiency of an inverter (a device that converts DC to AC) from just over 97% to a figure 1.6% higher. To look at it another way, losses are more than halved.

A SiC wafer with MOSFETs, such as those that are paired with diodes and used in the electrical systems of some Formula E racing cars
© Infineon Technologies (left), Rohm (right)

While such gains in efficiency may not appear to be that substantial, they can be if SiC is widely deployed. Suppose, for example, that the energy saving of 1.6% is applied to global electricity production, which totalled nearly 21,000 terawatt-hours in 2016, according to International Energy Agency statistics. This would equate to a saving of 340 terawatt-hours, which is close to the total annual electricity generation of the UK.

From a user's perspective, there can be an even bigger benefit than an increase in efficiency when moving to SiC devices: a reduction in the size, weight and cost of the electrical unit. As SiC devices can turn on and off far faster than those made from silicon, circuits are not limited to switching frequencies of typically tens of kilohertz. Hundreds of kilohertz are possible and this allows the use of far smaller, lighter and cheaper inductors and capacitors.

DELIVERING THE DIODE

In 2001, semiconductor manufacturer Infineon Technologies pioneered the first commercial SiC product with its SiC Schottky barrier diode, a device capable of blocking 600 volts. The SiC Schottky barrier diode, the simplest possible diode, is made by depositing a thin semiconducting film on a substrate, which is a thin, circular disc that provides a foundation for the device. After this, engineers process the coated substrate into thousands of chips, and on each one they add a metal contact to the front and back.

Such simple architecture cannot handle high-current pulses experienced in the field, so a far more complex design has replaced it. Further refinements have followed and today Infineon offers sixth-generation products for power supplies, as well as fifth-generation cousins for other applications. The voltage range has also expanded to include diodes with a 1.2 kV (kilovolts) blocking voltage.

When Infineon started manufacturing its diodes, substrates were just 50 millimetres in diameter. Back then, the company produced silicon devices on 125 millimetre or 150 millimetre substrates, making its production equipment ill-suited to making SiC devices.

SiC substrates have come a long way since then. They are now available in diameters up to 150 millimetres and the quality is far better, with the device-killing defects that plagued initial generations largely eradicated.

TARGETING THE TRANSISTOR

After the launch of the SiC diode, the race was on to make a commercial transistor with this material. By 2008, the first products hit the market but sales failed to take off.

According to Hong Lin, a senior technology and market analyst at Yole Développement, the first products were held back by the improvements made to their silicon rivals and, in general, circuit designers did not want to work with such a different product.

It took three more years before the market had a drop-in replacement for the silicon transistor: US-based company Wolfspeed's SiC, metal-oxide semiconductor field-effect transistor (MOSFET). This features a silicon dioxide insulating layer between the SiC film and the metal contact. Getting this device to market was a struggle: it took many years to remove the imperfections in the oxide layer so that current could flow freely.

Today, several companies manufacture SiC MOSFETs.

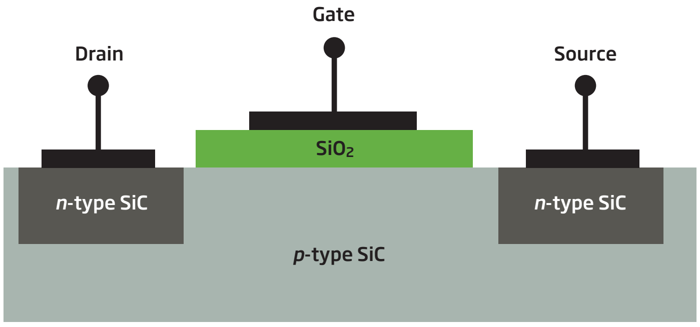
ELECTRICAL TERMS

- **Bandgap** – a measure of the energy that must be given to an electron so that it can contribute to electrical conduction between the valence band and the conduction band of a solid material (such as an insulator or semiconductor).
- **Diode** – a semiconductor device with two terminals that enables flow of current in one direction only.
- **Kilohertz** – a switching frequency of one thousand times per second.
- **Semiconductor** – a solid substance that conducts between an insulator and most metals. Its conductivity changes with the addition of an impurity or temperature. Devices made of semiconductors are essential components of most electronic circuits.
- **Substrate** – an underlying substance or layer for depositing semiconducting films.
- **Transistor** – a device that is used to amplify or switch electronic signals and electrical power.

SIC SCHOTTKY BARRIER DIODES AND MOSFETS

The simple architecture of a Schottky barrier diode is formed by sandwiching a film of semiconducting material between two metal contacts. When made of SiC, it can block hundreds of volts when a negative voltage is applied and conduct electricity with low resistance when a small positive voltage is applied.

The SiC film that lies at the heart of the device has a crystalline structure. This hampers current flow, because the four electrons in the outer shell of every carbon and silicon atom form strong covalent bonds and are not free to move. Therefore, to boost the current, engineers intentionally add a carefully chosen impurity – a material with a fifth electron in its outer shell. As this fifth electron is free to roam, it enhances electrical conductivity, thereby trimming resistance.



Material with this characteristic is known as *n*-type, because of the negative charges, and is used in the most common form of SiC transistor, the SiC MOSFET. In this device, a voltage is applied between the source and drain contacts, which are both connected to *n*-type regions of material (see figure above). Separating these regions is *p*-type material, formed by adding an intentional impurity with just three electrons in its outer shell. As four electrons from each atom are needed for bonding, there is an absence known as a hole. It spreads through the material, acting as a positive charge carrier. Applying a positive voltage to the gate drives away the holes beneath this region, creating an *n*-type channel just below the surface of the silicon dioxide (SiO_2) insulating layer. This channel allows a large current to flow when a voltage is applied between the source and drain. Removing the voltage causes the current to stop.

Japanese company Rohm, which released its device just after Wolfspeed, is pairing it with a diode in an SiC module used in the systems of electric racing cars made by Venturi, a competitor in Formula E. Meanwhile, Mitsubishi's SiC MOSFETs are used in Japan's electric trains, and STMicroelectronics' variants are going in the all-electric Model 3 Tesla.

One factor behind the recent success is the greater availability of 150 millimetre substrates that cut production costs, creating what Peter Friedrichs, Senior Director of SiC at Infineon Technologies, describes as a 'tipping point' in the market. In his opinion, the superior performance of SiC in some applications compensates for the higher cost.

Fuelling this growth in sales are the increasing use of solar power at high voltages and the roll out of fast chargers for electric vehicles. For both these applications it takes very little time to repay the additional expense associated with SiC devices.

THE GROWTH OF GALLIUM NITRIDE

GaN, which is used to make the LEDs that backlight device screens and increase the efficiency and lifetime of lightbulbs, has a similar bandgap to SiC. Its diodes and transistors work at lower voltages, such as 600 volts and below. As this market is bigger than that for higher voltages, where SiC serves, sales of GaN devices could eventually eclipse those of SiC. Today, however, annual revenue is only around $10 million, with devices used in power supplies in data centres and consumer applications.

Ideally, GaN devices would be made on GaN substrates, but this foundation is expensive and limited in availability, so silicon substrates are often used. This results in complications because the spacing of atoms in the silicon crystal differs from that in GaN. This mismatch causes strain to build up when growing a film of GaN on silicon, giving rise to imperfections that impair device performance. The trick is to trap these imperfections in a layer close to the substrate, before growing a device with high material quality on top.

Efforts to perfect this approach are well rewarded. It is not just that silicon substrates are far cheaper than both GaN and SiC, and more widely available in diameters of up to 300 millimetres. It is also that the GaN-on-silicon wafers can be processed relatively cheaply, and easily, in silicon fabrication plants (also known as fabs).

A team of engineers from Newport, South Wales, pioneered

Newport Wafer Fab is at the heart of a UK cluster that is developing GaN semiconductor devices and processes © Newport Wafer Fab

the GaN-on-silicon transistor. The Newport Wafer Fab team works at a foundry once owned by power semiconductor specialist International Rectifier, which used to develop GaN transistors from 2009. Device production then involved the growth of GaN layers on silicon at an external foundry in Minnesota, followed by the processing of this material into transistors at the fabrication plant in South Wales. Products were shipped to audio equipment manufacturers to use in high-end amplifiers.

In 2015, Infineon bought International Rectifier for $3 billion. After evaluating its global foundry capabilities, Infineon decided to sell the Newport facility. This led to the launch of the Newport Wafer Fab, which processes coated substrates into devices

SUPERIORITY STEMS FROM THE BANDGAP

	Silicon	SiC	GaN	Ga_2O_3
Substrate	Silicon	SiC	Sapphire, silicon or GaN	Ga_2O_3 or sapphire
Bandgap (electronvolt)	1.1	3.3	3.4	4.8 to 5.1
Breakdown voltage (millivolt per centimetre)	0.3	2.5	3.3	8 to 9
Thermal conductivity (watt per metre kelvin)	1.5	4.9	1.3	10 to 27
Dielectric constant	11.7	9.7	9	10
Mobility (centimetres-squared per volt-second)	1,200	800	900	300

Bandgap governs the performance of semiconductor power electronics devices (see the table above for values for common materials). In general, if a material has a higher bandgap, it will have a higher breakdown voltage and can be used in devices that operate at a higher voltage – or one that uses less material while handling the same voltage as a lower-bandgap equivalent.

Another important property is the thermal conductivity. For SiC, it is more than three times that of silicon and GaN, but much less than that for gallium oxide. A high thermal conductivity is a valuable asset as it increases the capability of a device to reduce temperature and thus run at a lower temperature. When SiC devices replace those made from silicon, this may go hand-in-hand with the removal of cooling units for the device, trimming cost, space and weight.

As well as the efficiency gains, the materials can operate at higher frequencies so other components can be smaller, which also leads to savings in size, weight and cost of electrical systems

on behalf of other companies. Newport Wafer Fab now plays a very active role in a regional cluster developing new GaN semiconductor devices and processes. At nearby Swansea University, researchers are developing processes to make GaN power electronics to create a technology that is available to those that partner with the Newport plant.

THE PROMISE OF GALLIUM OXIDE

Offering even greater efficiencies than SiC and GaN is Ga_2O_3, a material with a bandgap that is about 50% higher. A leading developer of these devices is Japanese company Flosfia, which is pioneering a novel growth technology to deposit films of this oxide on sapphire substrates, the most common platform for LED production. Initial results for diodes and transistors are very encouraging, including a new benchmark for resistance. Mass production of diodes will begin later this year, with the addition of MOSFETs slated for 2021. However, Lin believes it will be some time until these devices have significant commercial success.

ENHANCED EFFICIENCY

Devices made from these wide-bandgap semiconductors are taking significant market share from silicon devices, as engineers are moving away from using silicon. As well as the efficiency gains, the materials can operate at higher frequencies so other components can be smaller, which also leads to savings in size, weight and cost of electrical systems.

Every time you surf the internet, devices with wide bandgaps decrease the energy consumed by the server farms. When you buy an electric car, they are likely to lie at the heart of the electronics that power both it and the accompanying, growing network of fast-charging stations. Factor in the use of SiC in trains, the electrical grid, and solar and wind farms, and it's easy to see why these alternatives to silicon are going to play an ever-increasing role in electrical and electronic engineering.

UK: SUPPORTING PRODUCTION

UK companies are playing a significant role in the global wide-bandgap power electronics industry. The UK does not have a device maker, but has a foundry offering the processing of SiC material into diodes and transistors, and two companies making tools for the production of GaN and SiC devices.

Clas-SiC Wafer Fab in Lochnelly, Scotland, offers foundry services for producing devices from substrates coated with SiC films. This startup, led by engineers that gained valuable experience in SiC while working at Raytheon Systems' facility in Glenrothes, can turn a customer's design for a diode into a working device within four weeks, with an eight-week turnaround for a transistor.

The equipment at Clas-SiC can process 150-millimetre diameter material, the preferred size for the SiC industry. The facility can be used for small-volume, rapid prototyping, and production up to what is described as 'medium volumes'.

Production of SiC devices can involve the etching of trenches to define the device architecture. Processing equipment made by SPTS Technologies is capable of uniform vertical and tapered etches and can feature optical instruments to measure the depth of the trench during the etching process.

GaN devices grown on silicon may require the etching of holes through the entire structure, including the substrate or gently through GaN layers. SPTS's equipment can etch silicon at high speeds and provide slower, low-damage etching of GaN.

Oxford Instruments Plasma Technology, based in Yatton, has more than 30 years' experience in developing plasma deposition and etching technologies to produce various semiconductor devices. One of its great strengths, highly valued by the manufacturers of SiC and GaN devices, is producing processing equipment that can either remove or deposit material one atomic layer at a time. With this approach, when material is removed, damage to sensitive layers is minimised, ensuring high-performance devices. When material is added, such as when an aluminium oxide insulator is deposited, it is done so with tremendous accuracy, fine tuning the device's electrical properties.

A NEW CONTENDER FOR ENERGY STORAGE

The 15 MWh cryogenic energy storage demonstration plant at Bury commissioned in 2018 © Highview Power

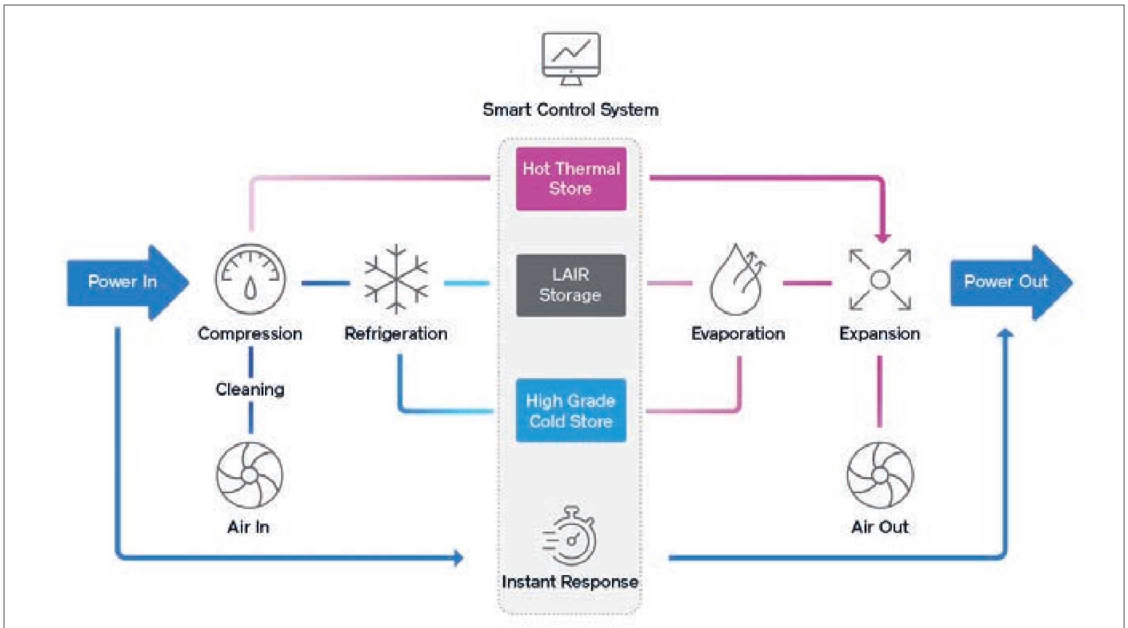
Energy storage has long been a challenge for those in the renewable energy field – what happens to unused energy generated by solar or wind power for example? A new system of storing it as liquid air could provide answers. Dominic Joyeux discussed how the system works with Highview Power's Dr Javier Cavada, CEO and President, Gareth Brett, Chief Technology Officer, and Professor Yulong Ding, Director of the Birmingham Centre for Energy Storage.

In years to come, 2018 may be seen as the year renewable energy came of age. At the beginning of the year UK government data showed that, for the first time, the 29% of electricity produced by wind and solar was more than the total produced by nuclear (21%). The increase means that low carbon energy sources now account for over half of all electricity generated.

However, a long-running challenge has been how to store energy at times when there could be shortfalls caused by the wind not blowing or the sun not shining. UK energy storage enterprise, Highview Power, is going some way to solve this problem. In 2018, it opened the world's first grid-scale cryogenic (liquid air) energy storage plant in Bury ('World's first liquid air energy storage plant', *Ingenia* 76). The plant has a capacity of 5 megawatts and can store 15 megawatt hours (MWh) of electricity, which is enough to power about 5,000 homes for around three hours.

STORAGE CONTENDERS

The main energy storage providers are pumped hydroelectric – 95% of global capacity – and lithium-ion batteries, which have been the fastest growing and account for most of the rest of the world's energy storage. However, although pumped hydro has a long lifecycle of between 40 and 50 years and very large storage capacity, its main drawback is geographical, requiring the correct topography and two large reservoirs, the building of



A process diagram showing the three stages of the producing, storing and recovering liquid air for generating power
© Highview Power

which can impact heavily on the environment.

In 2017, the potential of lithium-ion batteries captured the headlines when Elon Musk made a $50 million bet on Twitter that Tesla could build a 120 MWh battery storage in South Australia in under 100 days – if not, then the company would charge nothing for its construction. The state had been crippled by power shortages and took him up on his wager. Tesla delivered in 60 days and the result is the largest battery storage facility in the world, which supports and stabilises existing electricity supplies in the state.

However, although lithium-ion batteries seem to be the main contender for solving the renewable energy storage conundrum, they do have drawbacks. Lithium is relatively rare and its supply is controlled, in effect, by a handful of mining companies. Cobalt, which is needed for the cathode, is both toxic and rarer still. Although battery prices have dropped recently and they are a quick-responder when needed, batteries have relatively short lifecycles (between five and ten years), they degrade and they have a realistic limit of about four hours for harnessing large amounts of power.

Highview Power's cryogenic storage solution ticks many boxes including sustainability, cost, effectiveness and the fact that it has a small footprint and can be sited anywhere. The only box it had not marked until now was demonstration at large scale. Now, with plans to begin building two large cryogenic energy storage plants in 2019, that is set to be ticked too.

CLEAN COLD BEGINNINGS

Highview Power has created a whole new industry – clean cold. Co-founder Peter Dearman had an idea to build a reciprocating engine that was effectively driven by liquid nitrogen and could be used to power transport ['Delivering clean cold and power', *Ingenia* 68). In 2005, Dearman and power researcher Toby Peters founded Highview and tested the concept at the University of Leeds. In 2011, the engine part of the business subsequently branched off to form the Dearman Engine Company and has since found applications with transport refrigeration units and other cool-power projects.

In 2006, Gareth Brett, an electrical engineer with a background in utilities and banking, joined Highview and fundraised for a pilot plant. In 2009 he became CEO. By 2011, the world's first liquid air pilot installation was installed in Slough and connected to the grid with the help of a £1.1 million grant from the then Department for Energy and Climate Change. The plant had a 350-kilowatt charge with two and a half megawatt hours of storage. Now the technical fine-tuning of the cryogenic storage project could be done, ensuring that an actual plant would perform in the same way as the process model of the system.

The company partnered with Professor Yulong Ding, who in 2014 was appointed as the Highview Power/Royal Academy of Engineering Research Chair in energy storage at the University of Birmingham to further develop the cryogenic energy storage technology, alongside other thermally based concepts. He had worked with Highview since 2005 and had seen the potential for energy storage at very large scale. From 2006 to 2007, Professor Ding worked with Highview to invent and file patents for cryogenic energy storage and generation. Professor Ding's work helped develop the world's first research centre for cryogenic energy storage at the University of Birmingham.

HOW IT WORKS

The cryogenic energy storage system consists of three main components: a charging device that uses off-peak or excess electricity to power an industrial liquefier to produce liquid air; an

UTILISING THE CLAUDE CYCLE

Invented in 1902, the Claude Cycle has enabled production of industrial quantities of liquid nitrogen, oxygen and argon. It developed and improved the Hampson-Linde cycle, patented seven years before, which had introduced regenerative cooling and enabled the low temperatures required to liquefy gases. The main drawback with the Linde method had been the loss of temperature at the end of the expansion process. Georges Claude developed a cycle that used a turbo-expander to expand gas to lower temperatures for more efficient cooling. A turbo-expander operates in the same way as a turbine, expanding high-pressure gas so that it becomes lower in pressure and temperature and power can be recovered. A turbo-expander is used when its primary purpose is to cool gas, while a turbine is used when the purpose is to recover power.

Highview Power's system has adapted both the Claude and Linde cycles. Its charging process involves the compressing of air to ~ 12 bar (a unit of pressure), before it is cleaned and compressed further to about ~ 60 bar. The air is then fed into the top of the heat exchanger in the system's 'cold box', where it is cooled to around -100°C. At this point, some of the air is then bled off and expanded through a turbo-expander to cool it down further.

The remaining air that was not bled off continues through the heat exchanger. When it gets to about -180°C, it is expanded through a Joules-Thompson (JT) valve. It is at saturation point after it has finished expanding and a large portion of it condenses into its liquid phase. The remainder is a very cold gas.

The liquid and the gas enter a phase separator, which reduces the pressure, along with the air from the turbo-expander. Here, the liquid drops out and is sent to tanks, while the gas returns through the heat exchanger to the top of the system, cooling the incoming air along the way. Once it emerges from the heat exchanger, a compressor recycles it and returns it to ~ 60 bar before it rejoins the input air and forms a semi-closed loop.

Some of Highview's patents cover the capturing of high-grade cold and recycling it into the liquefier, an important step that doubles the efficiency of the liquefier and makes it economically viable.

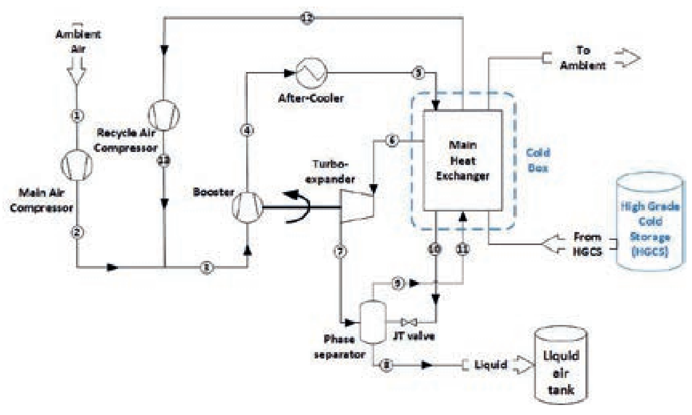


Diagram showing how Highview's pilot plant uses the Claude Cycle. In addition, the system uses recycled cold (shown in blue) input from its cold store. (The main air compressor, the circulating air compressor and booster, the compressor for compressing the main stream air into the cold box (heat-exchanger)) © Professor Yulong Ding

energy store where the liquid air is held in an insulated tank at low pressure, and a power-recovery unit where re-gasified liquid air is used to drive a turbine and generate electricity.

Ambient air is taken from the surrounding environment then using electricity it is cleaned, dried and refrigerated through a series of compression and expansion stages until the air liquefies. This process is based on a modified version of the Claude Cycle and can convert 700 litres of ambient air into one litre of liquid air [see *Utilising the Claude Cycle*].

The liquefied air – air turns to liquid when refrigerated to a sufficiently low temperature (~ -196°C at atmospheric pressure) – is kept in insulated tanks (acting as giant thermoses) at low pressure, which function as energy stores. When power is required, liquid air is withdrawn from the tanks, pumped to high pressure, reheated and then expanded. The resulting high-pressure gas is then used to drive expansion turbine generators to generate electricity. No fuel is burnt in the process, which results in the exhaust producing clean dry air.

Operating efficiency is enhanced by adding two stores. The first is a thermal store that gathers the compression heat generated during air liquefaction and is used for increasing air temperature prior to expansion in the turbine. The second is a proprietary cold store that captures waste cold from the regasification of liquid air while power is recovered and later delivers the cold into the liquefier to reduce power consumption – these measures close the thermal loop for cryogenic energy storage [see *Cold storage technology and materials*].

The separation of the power, storage and recovery components provides flexibility in the system's design. Because power and energy are independent of each other, requirements can be tailored so that clients can decide how much of a tank they want to fill, how much energy to store and then how quickly it needs to be emptied. This modularisation of the process enables different configurations and solutions to suit each customer.

DEMONSTRATION PLANT

In June 2018, these elements were brought together in the cryogenic energy storage plant in Bury. The 5 MW/15 MWh

1. Liquid air storage 2. Cryo pumps 3. Power turbine and generator (5 MW) 4. Heat exchanger containers 5. High grade cold stores © Highview Power

COLD STORAGE TECHNOLOGY AND MATERIALS

High-grade cold storage plays a key role in reducing the power consumption of the air liquefaction process and hence improving the round-trip efficiency of cryogenic energy storage. The first consideration to make when compiling the liquid air system's components was the selection of appropriate cold storage technology. Packed-bed (a hollow tube, pipe or other vessel that is filled with a packing material) was chosen because it serves as both a cold storage device and a heat-exchanger. This selection was based on the technology's maturity, cost, performance and scalability.

The other major selection considerations were to do with the cold storage materials. The density and specific heat capacity of cold storage materials need to be as high as possible to increase the energy density of the store and reduce the physical size – and therefore cost – of the containment structure.

The material's thermal conductivity should be sufficiently high to ensure that the charge and discharge speeds can be achieved quickly. It should also be able to minimise the temperature gradient inside the individual particles to ensure efficient heat transfer.

The material's mechanical properties needed to be strong enough to withstand thermal stresses due to the system's repeated thermal cycling. It was also required to cope with the hydrostatic stress due to packing. After much testing, gravel was chosen as the cold storage material. The gravels picked had a thermal conductivity of ~ 1.8 W/m.K, specific heat capacity of 0.71 kJ/kg.K and a density of 2600 kg/m^3. The added advantages of the gravel were its low cost and the fact that it could cope with both ambient and cryogenic temperatures.

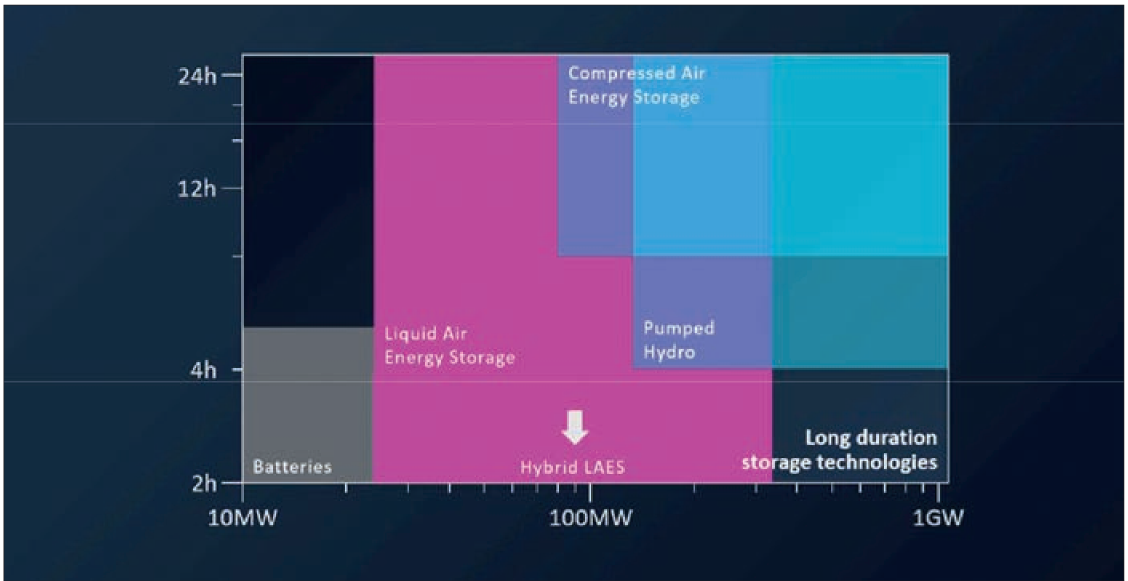
storage unit was sited at Viridor's Pilsworth Landfill Gas Generation site to convert its waste heat to power, thereby increasing the system's efficiency ('efficiency' measures the percentage of electrical energy discharged compared to the amount used to charge the storage system). Cryogenic storage systems could also use industrial waste heat and cold from applications such as thermal generation plants, steel mills and liquefied natural gas (LNG) terminals to improve the standalone efficiency.

Building the demonstration plant allowed Highview Power to test the best economies of scale and figure out where economic efficiencies could be made. One of the company's guiding principles when developing the energy storage system has been to use proven components from mature industries that are tried, tested and available.

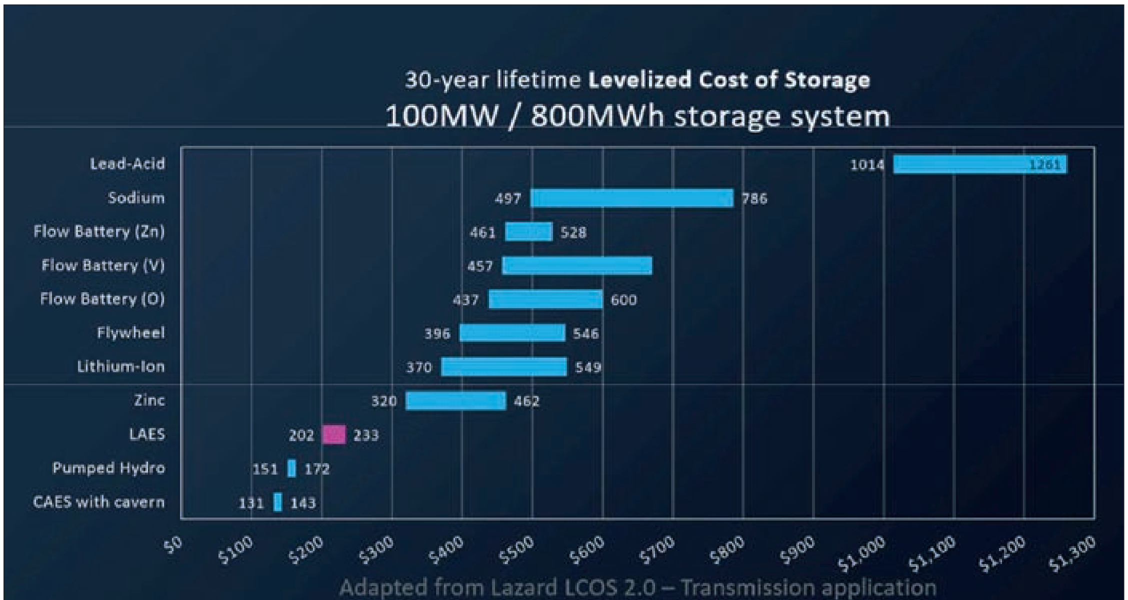
The energy storage equipment that the company incorporates is already globally used for the bulk storage of liquid nitrogen, oxygen and LNG – such as heat exchangers, packed-bed storage units and cryogenic insulation. This way it can confidently state the lifespan and efficacy of each plant's hardware – Highview will guarantee a 30-year lifetime for its systems. The end-of-life recycling characteristics of the system are also favourable as most of the tanks and equipment are made of stainless steel with some copper in the generators; apart from lubricating oil, Highview states that the process uses nothing toxic.

The last piece of the jigsaw to be fitted before the first big sale was to improve the response times when supplying energy to the grid. For this purpose, supercapacitors and flywheels have been added to the Pilsworth plant and response times are now measured in seconds.

Highview Power sees cryogenic energy storage as being most useful in supplying the electricity grid via reserve, regulation and balancing. The idea of reserve is to keep spare capacity in the system and keep a cache of stored energy.



A diagram showing the energy storage options available in terms of time and capacity © Highview Power



This chart shows the cost of cryogenic energy storage (LAES) provided by Highview Power's system over 30 years compared to other forms of energy storage © Highview Power

The company can scale-up and incorporate three or four extra tanks of stored energy for this purpose. Effectively, balancing is about moving energy from one time slot to another. Regulation entails keeping the frequency constant so that the plant is matching in real time, second by second, supply with demand – stabilising frequency.

WHY NOW?

In September 2018, Dr Javier Cavada was appointed as CEO and he sees the future storage capacity of liquid air increasing from five hours to perhaps 20 hours and then a couple of days or even weeks. Liquid air can be kept for months until eventually the air in it boils off and then must be topped up with liquid air; usually, the system cycles daily and never reaches this point. He also feels that the 50 megawatt size will, thanks to the modularity of the system, increase to 100 megawatt. In five years' time, he thinks that there will be around 20 Highview cryogenic energy storage plants around the world supplying and storing 10 gigawatt-hours of energy.

Long-duration storage has always been critical to enable the wider deployment of renewable energy and overcome the intermittent nature of solar and wind energy. It seems that cryogenic energy storage can provide that and will soon be smoothing out the peaks and troughs of renewable demand in the UK and wherever it is needed.

BIOGRAPHIES

Dr Javier Cavada is CEO and President of Highview Power. He joined the company in 2018 after 17 years in leadership positions at Wärtsilä Corporation, including executive roles in China, Italy, the Netherlands, Spain, and Finland.

Gareth Brett is Chief Technology Officer at Highview Power. He joined the company in 2006 and helped lead it in taking cryogenic energy storage from concept to market-ready technology. From 2009, he served as CEO before being appointed Vice Chairman and Chief Technology Officer in 2018.

Professor Yulong Ding is Director of the Birmingham Centre for Energy Storage. In 2014, he was appointed as the Highview Power/Royal Academy of Engineering Research Chair in energy storage at the University of Birmingham. He also holds the founding Chamberlain Chair of Chemical Engineering at the university.

COMMUNICATION AT THE SPEED OF LIGHT

Data transmitted through LED light sources could transform online connectivity, while potentially underpinning the rapidly expanding Internet of Things. Neil Cumins spoke to Professor Harald Haas, Professor of Mobile Communications at the University of Edinburgh and Co-Founder and Chief Scientific Officer of pureLiFi, about the future of data transfer using this technique.

History has many 'what if' scenarios and the development of radio communications may have inadvertently prevented another technological breakthrough. In 1880, Alexander Graham Bell developed a photophone that used a beam of light to transmit messages across the visible light communications (VLC) spectrum. However, subsequent advances in radio wave technology eclipsed Bell's work and the 20th century was consequently dominated by communication across the radio frequency (RF) spectrum.

Fast forward to the present day and another VLC breakthrough is imminent. Engineers have been looking beyond RF wireless cellular communications and Wi-Fi to satisfy our spiralling requirements for high-speed data transmission. Unlocking the potential of high-frequency, short-wavelength VLC bands has become crucially important as global data traffic continues to rise, with light fidelity's (Li-Fi) potential currently being tested in proof-of-concept trials around the world.

LEDs make the concept of a wireless data network provided by existing light sources possible. All digital data is coded in binary form – zeroes and ones – which also correspond to the status achievable by a light element. By turning a light on and off within a few dozen nanoseconds, it is possible to transmit huge amounts of data

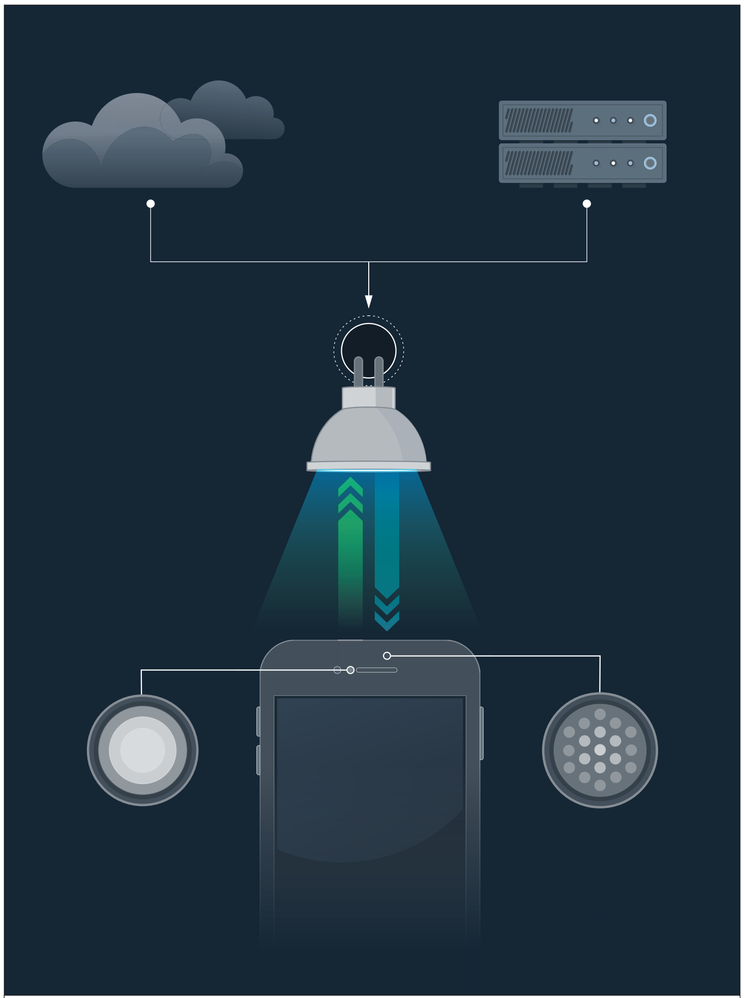
Li-Fi is an alternative to Wi-Fi that uses existing light sources to transfer data. While not widely adopted yet, proof-of-concept trials in real-world scenarios are demonstrating the benefits that can come from using the technology © pureLiFi to nearby objects. The human eye is unable to identify any fluctuation in light levels, but any device equipped with a compatible photodiode receiver can detect the presence or absence of individual light photons.

Rather like the triangulation of mobile devices, where a series of cellular base stations and localised micro-cells offer connectivity at any given moment, Li-Fi data is distributed through coordinated transmissions from various light sources. Dense networks with multiple cell sites improve achievable data rates, while creating a wider network of coverage. For instance, a table lamp and spotlight at opposite sides of a room could each distribute their own arcs of light, with algorithms seamlessly handing over from one device to another as the data receiver, such as a smartphone, moves between them. The frequencies used to transmit Li-Fi data are almost completely resistant to interference from sunlight, so low-energy streetlamps could provide a stable connection for people walking down a pavement, even on a bright day.

LIGHT BENEFITS

Li-Fi offers several advantages, as Professor Harald Haas from the University of Edinburgh explains: "It's secure, simply because light doesn't go through walls. Somebody on the street would find it hard to build an optical system to intercept that light … whereas with Wi-Fi, data interception can be achieved from a safe distance. That makes Li-Fi ideal for offices, banks and insurance companies, where data sensitivity is very important." He cites the example of manufacturing facilities, where terabytes of data could be transmitted from robots to the cloud: "nobody outside the halls could read the signal and write down the data sets, because manufacturing facilities rarely have windows."

Li-Fi also enables precise location services, which could be used to build a histogram of movement that artificial intelligence and machine learning could use to determine typical user behaviour. For example, says Professor Haas: "if someone is meant to be in a meeting room every Friday at 10.00am but there's one Friday where they are in a secure server room, the system could flag an anomaly. You might view that as 'Big Brother is watching', but from a cybersecurity perspective, the enemy is often inside the system."



The key building blocks of a bi-directional Li-Fi communication link consist of an infrared transmitter and a photodetector, integrated into a mobile device. A lightbulb at the other end serves as a wireless access point and also has an integrated photodetector to receive data. The lightbulb is connected to a data server or cloud architecture, which provides a connection to the internet © pureLiFi

Data transmitted across light-based communications links also avoids interference with electrical equipment, which means Li-Fi is suitable for use in environments where RF transmissions are restricted. For example, an uninterrupted data flow could be provided through the reading lights on aeroplanes or through existing ceiling lighting in hospitals.

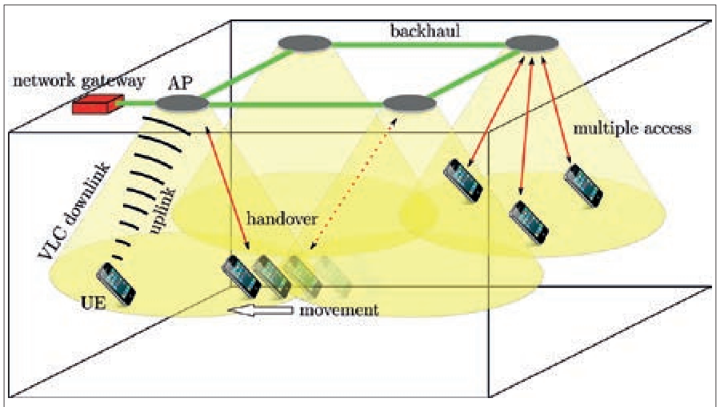
Li-Fi operates well in low light conditions, as Professor Haas explains: "there's a minimum amount of light required depending on the respective photo-receiver technology.

LEDS

Any LED light, including status lights on microwaves or fridges, torches, car headlights or streetlamps, can be turned into a high-speed data transmitter, whether organic, micro, different colour or single device white LEDs.

Professor Haas's research team has used a single colour LED purchased for less than 10 pence to transfer more than 4 Gbps (billions of bits per second) of data – faster than the best speed achievable with the latest Wi-Fi systems, which top out at around 867 Mbps (millions of bits per second).

The achievable data rate performance of Li-Fi significantly depends on the light source and the detector. The bandwidth of each technology is different and ranges from 2 MHz (megahertz) in the case of phosphor-coated white LEDs to 1 GHz (gigahertz) in the case of micro LEDs. Current low-cost commercial white light LEDs are composed of a blue LED chip and a layer of a phosphorous material that converts some of the blue photons to yellow photons; these mix with the blue photons to create white light. Unfortunately, the phosphorous coating reduces the bandwidth of the device. As a result, the maximum data rate is in the region of tens of Mbps. This can be eliminated by using different colour LEDs such as red, green or blue LEDs, which has two effects: there is no need to use the coating as light can be mixed into any colour including white, and as a consequence the bandwidth is significantly increased by one or two orders of magnitude; and each colour could carry independent data and as a result, the data rate linearly scales with the number of colours. Therefore, multicolour LEDs can achieve data rates of 50 Gbps (assuming approximately 12 colours) and higher. Lastly, the automotive sector uses white light sources that use laser diodes to produce white light that is harmless to eyes. It is conceivable that these lighting devices will be introduced to the consumer lighting market within the next few years and, as laser diodes have much higher bandwidth than LEDs, this would mean that future lightbulbs could transmit data at speeds in the Tbps (terabytes per second) region.

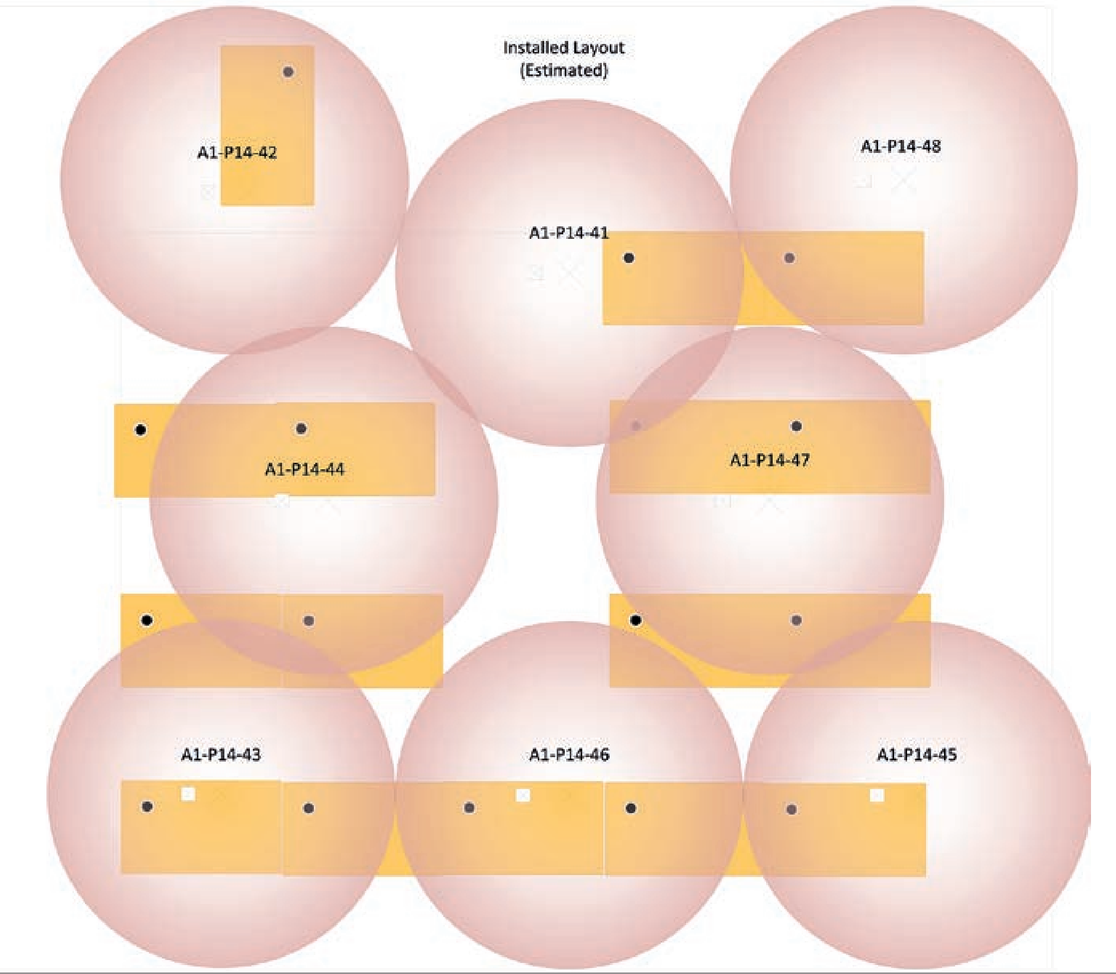


This diagram shows how ordinary LED lightbulbs become Li-Fi access points. They are connected via a high-speed data backhaul, such as power-over-ethernet (PoE), which means that power and data is supplied simultaneously by one connection that can provide up to 60 watts. As lamps are not connected to the main power supply, entire buildings can be fully equipped with PoE lighting. In the case of retrofitting, a different technology, such as powerline communication, would be more advantageous to avoid new cabling. This uses the main power supply to distribute data

As a consequence, one of the existing challenges in the design of Li-Fi systems is the receiver. What's important is that a signal is received optimally at the receiver. A typical photodetector device takes the fluctuating light photons, which carry the information, and converts them into an alternating current. That needs to be converted into voltage signals using a transimpedance amplifier – an operational amplifier that takes the alternating current and turns it into an alternating voltage signal that can be processed by analogue-to-digital converters." However, there have been significant advances in the research of new detectors and optical components recently. Several photodetector technologies are in development, including highly sensitive single photon avalanche diodes that count individual photons and need almost no light input into the receiver and no transimpedence amplifier. However, this particular detector can be easily saturated by ambient light. Other photodetector technologies are characterised by the trade-off between bandwidth and sensitivity. Generally, a larger detector area can collect more photons and achieve higher receiver power, but this also means that the detector has a high capacity that limits the bandwidth. To overcome this limitation, optical concentrators can be used in conjunction with small area detectors. However, optical concentrators reduce the bandwidth of the system, which is an issue to overcome. Therefore, dealing with low light levels is still an ongoing area of research and development. Sunlight or bright light interference can be less of an issue: using appropriate optical and electrical filtering techniques in combination with appropriate digital data encoding techniques, the impact of strong sunlight interference can be reduced to less than 5% degradation of achievable data rates.

LI-FI IN REALITY

Li-Fi is currently being used in more than 130 real-world deployments in over 23 countries, including one notable example at a high school in Ayr. As the first school in Scotland to adopt Li-Fi technology, Kyle Academy has a classroom equipped with eight ceiling-mounted LED lights that provide speeds in excess of 340 Mbps (millions of bits per second). As well as providing high-speed data access for pupils and teachers within that particular room, the introduction of Li-Fi has improved Wi-Fi speeds in neighbouring rooms, because fewer people were using the available RF bandwidth. This means that losses caused by data collisions (when devices try to get access to the Wi-Fi channel) have been reduced,



This diagram shows a real-world Li-Fi installation in a school classroom. Usually, there is at most one Wi-Fi router per room, but Li-Fi makes it possible to have almost one wireless router per desk yielding a much higher data density. The Li-Fi network installed here consists of eight Li-Fi access points mounted in the ceiling (the circles) to provide coverage to the students' and teacher's desks (the yellow boxes)

resulting in a significant efficiency improvement in Wi-Fi. In the past few years, Wi-Fi has worked as a 'pressure relief valve' for 4G data traffic through data offload. This has aggravated the congestion issue in Wi-Fi in crowded places, such as schools. The school trial has shown that Li-Fi can work very effectively as a powerful 'pressure relief valve' for data offload from Wi-Fi.

In contrast to point-to-point optical wireless communication, which uses VLC, a Li-Fi system is defined as a fully networked, multiuser, bi-directional cellular communications system (see image above). It includes multiple access points that form cellular networks, which are constructed of many ultra-small communication cells, to provide high-data-density wireless communication services to multiple mobile users simultaneously. The Li-Fi network supports handover when users move across different light coverage regions.

In addition, connections between access points and network gateways are essential to enable cooperation and establish connection to the wider communication network. The Li-Fi downlink piggybacks on existing LED lighting systems, which are becoming increasingly popular. The systems also comprise of an optical uplink – the link between the mobile terminal and the access point. Since using visible light in the uplink may cause distraction to the mobile user, the use of the infrared spectrum is deemed most appropriate for this link direction as there is no interference between uplink and downlink and simultaneous communication links can be established.

Since the lighting system now has two primary functions – lighting and mobile connectivity – there is a natural trade-off when it comes to installation. In some instances, the communication requirements are different from the lighting requirements, which would demand a different lighting layout. However, research has shown that as lighting typically 'follows' users, the optimum lighting layout mostly leads to almost optimum communication performance in typical indoor situations. Also, it is important to be able to communicate while the lights are off, so the communication performance must be largely agnostic to the dimming levels. Professor Haas's team's work has shown that this can be achieved by designing new digital modulation techniques such as enhanced unipolar orthogonal frequency division multiplexing (OFDM). This can significantly reduce the emission of photons that are not used for communication purposes by superimposing multiple parallel data streams in time and frequency in such a way that the constant light output, which primarily serves to illuminate, can be reduced to close to zero. Moreover, OFDM divides the entire bandwidth into multiple subchannels that can be grouped together to form a data stream. This provides multiple advantages. One of the most important ones is that each subchannel can be treated independently. Typically, there are subchannels that offer good conditions and others are highly attenuated, especially at the upper region of the bandwidth. With OFDM it is easily possible to vary the transmission rate per subchannel to adjust to the varying channel conditions and always ensure that the bandwidth is used optimally. This is an important requirement for mobile use cases where the channel constantly and randomly changes. If communication is required when the lights are off completely, such as in an aircraft cabin at night, the integration of infrared light sources alongside visible light LEDs provides a straightforward solution.

Adoption of existing optical communication technology for Li-Fi is possible to a certain extent. For example, remote controls that use infrared light for low level and low data rate control are based on pulsed modulation techniques, which can be limited in high-speed mobile communication environments. Reflections from walls and objects cause interference and line-of-sight cannot be guaranteed at all times. For example, with a mobile phone that constantly changes orientation, the Li-Fi system must be designed to be robust to such random changes. As a consequence, it demands different optical communication technologies than used in applications where there is always line-of-sight between the transmitter and the receiver such as TV remote controls, which directly point to the TV, or outdoor long-range optical links installed on roofs or masts, or ground-to-satellite optical communication systems, which use tightly focused lasers.

THE FUTURE FOR LI-FI

According to Cisco Vision, by 2020 96% of all mobile data traffic consumption will be indoors. Li-Fi's potential for internal data transmission represents the greatest driver behind the technology. The 2.4 GHz (gigahertz) industrial, scientific and medical (ISM) band (used for RF transmissions) had become so congested across its 150 MHz (megahertz) of bandwidth that new bandwidth in the 5 GHz region has been unlocked to provide additional bandwidth of about 500 MHz. Even then, the plethora of electromechanical devices attempting to use this bandwidth cause data loss, interference and slow transfer speeds, which are incompatible with the always-on, ultra-fast connectivity required to transmit the Internet of Things' exponentially increasing data volumes.

Professor Haas believes that Li-Fi will go hand-in-hand with the Internet of Things, where formerly passive devices perform specific tasks using internet connectivity. From self-replenishing fridges and app-connected bathroom scales through to autonomous vehicles and remote surgical procedures, an estimated 125 billion devices will require online connectivity by 2030. The RF wavelengths currently being used are considered slow and congested to adequately service these vast amounts of data and also provide the required quality of service, such as low-latency requirements for mission-critical applications. Even the forthcoming 5G infrastructure may be insufficient. By contrast, Li-Fi has around 780 THz (terahertz) of bandwidth ready to be used, across a light spectrum 2,600 times larger than the entire RF spectrum.

It seems that Li-Fi is inevitable given the continued growth of mobile data transmission. However, this technology will only move into the mainstream on a larger scale once original equipment manufacturers start adopting Li-Fi technology in their devices, in the same way as they have previously introduced 4G and Bluetooth. Professor Haas views Li-Fi as complementary to 5G, rather than a replacement: "If you have your device in your pocket, you'd use Wi-Fi for message notifications, because Li-Fi cannot penetrate fabrics very well. It's a question of where the technology is best used. If the device is taken out of the pocket and has a good connection, you would use Li-Fi. If you are in areas where there is no light coverage, or the lights are completely off, obviously you would have a seamless handover to Wi-Fi. Li-Fi is complementary to Wi-Fi, in the same way Bluetooth and 4G work alongside Wi-Fi now."

Professor Haas believes the Li-Fi revolution could be imminent: "Given that we are on the pathway to developing a standard in microchips that allow integration and scalability, I reckon people will be able to buy Li-Fi-enabled products within the next two to three years." That is worth remembering next time you turn on a lamp or watch a standby light glowing on an electrical device.

BIOGRAPHY

Professor Harald Haas is Professor of Mobile Communications at the University of Edinburgh and Co-Founder and Chief Scientific Officer of pureLiFi. He is also Director of the LiFi Research and Development Centre at the University of Edinburgh. He first introduced and coined Li-Fi in a TED Global talk in 2011. Subsequently, Li-Fi was listed among the 50 best inventions in *TIME* magazine. His two TED Global talks have been watched more than five million times.

Air Marshal Susan Gray CB OBE FREng

A ROLE MODEL FOR THE NEXT GENERATION

Join the Royal Air Force (RAF) as an engineer and you can expect to take on many roles. For Air Marshal Susan Gray CB OBE FREng it has meant not just the obvious task of keeping aircraft in the air but also responsibility for procurement, supporting the RAF's response to emergency relief, taking charge of marching bands, and her current task of preparing the headquarters for the future. The RAF's centenary in 2018 also gave her an opportunity to raise the profile of engineering among young women.

Gray wanted something more than a straightforward technical role, something that involved working with people as well as machines, so rather than signing up to be a technician, she opted to sign on for six years and begin officer training

Oversight of marching bands is probably the last task a young engineer starting a career in the Royal Air Force (RAF) would think their job would involve. However, Air Marshal Susan Gray CB OBE FREng took on the role as part of her growing responsibilities as she rose through the ranks. She has recently been promoted to the rank of Air Marshal – making her the most senior female military officer in the Armed Forces and the UK's first female three-star officer in the process – but, as Air Officer Commanding Number 38 Group, RAF Chief of Staff Support and Chief Engineer for Air Command, Gray managed 'a one-stop shop', as she puts it. Along with the RAF's musicians, she handled ground engineering, logistics, aviation medicine and catering. Whenever the RAF had to set up somewhere, Gray's team led the way and set up operations before the squadrons could move in and get to work. She will soon take up the role of Director General of the Defence Safety Authority.

Before she took over 38 Group, Gray held a variety of engineering roles, keeping a miscellany of aircraft in the air, along with such tasks as managing media relations and working on a new generation of body armour, helmets and combat clothing for frontline troops.

A PEOPLE PERSON

A career as an RAF engineer was not Gray's plan from her early years. There was no family background in the services or in engineering, although she was interested in how things worked. Gray jokes that in the family her father was not technically minded, so it was down to her and her mother to sort out anything in the home of an 'engineering' nature.

It was the RAF's interest in attracting young recruits that set Gray on her career path. Around the time that she was thinking about what to do after school, a friend decided to try to get into the RAF. Determined to avoid falling into a nine to five office job, Gray decided to follow suit. "I said OK, I will see if they will sponsor me to go through university and if I can get through the selection test, which I did, why wouldn't I?" The air force nudged her in the direction of engineering. "The fact that I ended up doing engineering wasn't a complete fluke. I did enjoy it, but I was probably better at taking things apart than I was at putting them back together."

Gray wanted something more than a straightforward technical role, something that involved working with people as well as machines, so rather than signing up to be a technician, she opted to sign on for six years and begin officer training. A condition for getting an RAF bursary for officer training was that Gray had to study for a degree, so she chose physics and electronics. As she describes it, her decision to do that was "probably purely mercenary". Then again, she laughs, 33 years later "it was not a bad investment by the RAF".

People and engineering came together on Gray's first posting, working on VC10 aircraft. She faced "the challenge of being the only officer awake" when an aircraft made an emergency landing. "Suddenly you are the incident commander, rushing out to an aircraft that is on the runway," she says. This meant managing a team of engineers and technicians, and was certainly no office job. "You think, 'this is quite good fun'," she recalls. "Let alone the fact you actually had a job to do, it was around leading and managing people."

One thing about an engineer's life in the RAF is that Gray was constantly on the move, geographically as well as within the RAF, as she moved up the ranks and from posting to posting, with tours in Iraq during the Gulf War and Northern Ireland. After a spell as an Engineering Officer on VC10, and Chinook, Puma and Wessex helicopters, she returned to study at Cranfield University to add a master's in aerospace vehicle design to her qualifications. By coincidence she was working on her thesis on 'conceptual design of a fighter aircraft' at the same time as the RAF was building the Eurofighter, its next generation of aircraft. "It was quite interesting to be able to compare and contrast," she says.

VARIED ROLES

While keeping aircraft flying has dominated Gray's engineering career, the diversity of an engineer's life in the RAF means that there have been other activities. For example, she managed the Combat Clothing Project Team, which looked into body armour and helmets. "We went out to Afghanistan to see how the soldiers were using the equipment and where we thought we could make improvements to it," she says. "That was the last time I was in a war zone."

After that brief excursion, Gray's next engineering venture was overseeing the department delivering remotely piloted air systems. Her role included signing off the authorisation for the first flight of Taranis, a demonstrator project for a remotely operated 'stealth' air vehicle that could avoid radar detection. "We were trying to prove that we can fly it

Before the Taranis unmanned combat aerial vehicle could makes its maiden flight in 2013, Gray had to certify it as being 'fit to fly' on behalf of the RAF. Working with BAE Systems, she had to check that the technology demonstrator achieved the specified 'software integrity level'. Gray and her team of systems engineers had to subject the technology to fault-tree analysis © RAF

safely," says Gray. "It was a great technology demonstrator and it worked." The project partnered with BAE Systems, which is taking the work forward. One of Gray's roles on Taranis was to certify it as being fit to fly for the first time in Australia. "I was a bit disappointed in not being able to actually be there, but I had to sign the paperwork and then watch other people watch it. Fortunately it all worked well."

Gray's time in the RAF has not been all engineering. In one post, "probably my only role where I didn't actually require any of my engineering skills", she was Head of Media and Communications at the RAF's headquarters. "It was illuminating," she says. One of her achievements in that job, and more generally in the RAF, seems to have been to keep herself out of the media. "I do try quite hard," she says laughing, "partly for security."

It certainly would have been hard to remain under the radar given Gray's role during RAF100, the air force's centenary celebration. During the year, she gave the prestigious Amy Johnson Named Lecture 2018 at the Royal Aeronautical Society, during which she spoke about women in aviation, paying tribute to the inspiring women that came before her, and reflected on her own 33 years in service – including becoming the first and only woman two-star engineer in the force.

The centenary also weighed heavily on the engineering side of 38 Group, which transported the ground display of aircraft that toured the country with a science, technology, engineering and maths (STEM) roadshow, starting at Horse Guards Parade. This was timed to coincide with the historic flypast over London of 100 aircraft in July 2018. The RAF's musicians also had plenty to do during the centenary. "I don't know what we would do without them because they do absolutely maintain morale," says Gray. "When you see them doing celebration concerts and supporting parades, it is very moving."

Gray had taken over as head of 38 Group around the time that it took on many of the RAF's 'behind the scenes' tasks, such as leading the infrastructure for the whole of the air force. This change was down to the RAF's pursuit of greater efficiency. "We have centralised the logistics, some of the ground engineering functions and medical support, and the catering support, even the musicians, into 38 Group," Gray adds. The objective was to get to a position where every group did not have to maintain all of the skills required to fulfil its main role. "We support all the other groups in their activities," says Gray. "So we are always busy, always in demand."

The Red Arrows fly over central London as part of the RAF100 fly past in July 2018 (left), while RAF service personnel celebrate the centenary outside Buckingham Palace © Claire Donovan (left), RAF (right)

At any one time, the 3,000-strong 38 Group could be anywhere. "We were in about 25 different locations around the world at one point," Gray says. "Whether we were supporting from an operational perspective or from a training perspective, there were lots of exercises. At the drop of the hat, we were required to support tornado or typhoon aircraft wherever they were around the world, or aircraft on hurricane relief operations."

The RAF is called in to support relief operations because, as Gray says, "we can get there quickly". For the people in charge of relief activities, the work is back at base in 'the ops room', managing service people out in the field. "The last relief operation was in the Caribbean," explains Gray. "Several of my teams were deployed. Communications engineers went to set up communications. Medics were flying between islands, wherever they needed to be. As the first in, they could set up a headquarters. 38 Group wasn't running the operation, but without them being there, there wouldn't have been an operation." While this was happening, the group also had to support the RAF's standing tasks in Cyprus and the Falklands. Relief work sits alongside as one of the RAF's various 'contingencies', work that in the past took on mad cow disease and fire service strikes, and more recently has involved Brexit planning. International agreements already cover air movements, Gray explains, so if Brexit does cause disruptions, they are more likely to affect the RAF's road operations. At 38 Group, Gray ran a squadron of drivers moving articulated lorries to support the RAF's operations in the Balkans, for example.

After two and half years in charge of 38 Group, Gray now runs the future operating model study. Again, her sense of irony comes in as she recounts how she landed her latest assignment. This may be one of those desk-based jobs that she vowed to avoid, but, with just three months to complete the work, this desk job will not last too long. During an earlier reorganisation, she objected when someone threatened to take away bits of her operation. "I got a bit hot under the collar and basically said 'you cannot do this in isolation, you need to look across the whole headquarters'." That observation came back to haunt Gray; towards the end of her posting at 38 Group, the message came back: "Do you remember what you said? Well we would now like you to go and do it."

FORCE DEVELOPMENT

Working out of a small office at RAF High Wycombe, the air force's main base in the UK, Gray's task is to put the RAF's operations and abilities under the microscope. "We quite often review our structures and how we operate, but it is quite significant now because the Ministry of Defence (MoD) is going through a transformation." This follows Lord Levene's 2011 independent report into the MoD's structure and management. "The main premise was that we would move much of the running of each of the services on a day-to-day basis out from London to the main headquarters." Gray's current task is to review progress and to ask if the RAF has got the right resources: the right people with the right skills, and the right processes and governance in place to deliver on those tasks.

One question she is addressing is the approach to career development, which has put her in a good position to understand how the RAF works. The traditional pattern of two-year postings is a great way of ensuring that officers get to see how the RAF works from all angles. "Throughout our careers as engineers, we have built up our operational experience from being junior engineering officers on

When the UK goes into action to provide humanitarian relief after natural emergencies, the RAF's speed means that it is often the first to reach distant locations. As head of the RAF's logistics operations in 38 Group, Gray was in charge at the time of the latest operation, when Hurricane Irma hit the Caribbean, killed over 130 people and left thousands of people without shelter and power, facing hunger and disease. 38 Group loaded helicopters into the back of C17 transport aircraft © RAF

squadrons and senior engineering officers, then being the chief engineer on a station, responsible for all the engineering, whether it was aircraft, ground equipment, vehicles or anything," she says. But is two years long enough? "We have all recognised that you spend the first year trying to find your feet and operating in the second year, but most projects and programmes are longer than two years. It is quite hard to see something through from initiation to completion."

Along with looking at the way in which the RAF organises itself, as Chief Engineer for Air Command Gray naturally has thoughts on possible changes on the engineering front. "We need to become faster and more agile at developing new technology," she says. In particular, her view is that, when working with industry, the RAF has to be more innovative and willing to take risks. When it comes to trying new ideas, she wants it to think "it might work, it might not but let's give it a go. If it doesn't work then that's fine, move on. We are starting to become a lot more flexible and responsive in how we develop and procure new technology."

Gray attends the RAF Halton graduation from Phase 1 training. Many of the graduates were young apprentice technicians at the start of their careers in the RAF © RAF

A CAREER FOR YOUNG PEOPLE

In her previous role as Head of the Engineer Branch and Trades, Gray was responsible, along with two other Air Vice Marshals at High Wycombe, for training and recruiting engineers and technicians into the RAF. They worked together to develop the RAF's approach to education and recruitment in STEM. "Like most industries, we have struggled to recruit over the last 10 years," says Gray. Finding engineers is an important task for the RAF: add the air force's 800 engineers to its 15,000 technicians and you have about half of the RAF's 31,000 headcount.

RAF100 was a great opportunity to tell the world, especially young people, about the RAF and what it does. "I couldn't have had a better advertising campaign," says Gray. "Anybody who doesn't know what the RAF does must have been overseas for a year." Gray was especially keen to exploit RAF100 as an opportunity to make the case to young women: "I'm passionate that girls and young women should feel that they can do engineering and maths." She describes last year as being "pretty transformational", particularly when it comes to the growing confidence among young women in their ability to do engineering.

The RAF ran a series of school events throughout RAF100. "By the end of the year, all our courses were oversubscribed," she explains. "Parents are asking us if they can come again next year. We would love to carry on and we will find a mechanism for doing some of it. We have a youth engagement and STEM hub that we are building on the back of RAF100."

Gray has also embedded the RAF's STEM activities in assessing the careers of engineers. One of her roles, she explains, is to write the principles for how the RAF promotes people in the engineering branch, which do not allow engineers to get by with simple box-ticking exercises. "I am looking for people that actively recognise the need to recruit and retain personnel. I want people who are passionate about what they do to pass that passion on. It is not enough for people to write 'I am a STEM ambassador' in their annual assessment appraisal," says Gray, "I need to see what you have done. Those that have actively run courses or done stuff will go further up the pecking order."

This is not a directive that Gray just wants others to follow. "I have a couple of people who I can say that I have directly recruited, which is quite unusual. You don't normally get to see the end result."

Recruitment is one of many changes in how the RAF manages people that Gray has seen since she joined 33 years ago, almost exactly a third of the air force's existence. It was even the Women's Royal Air Force when she signed up. That changed soon after she joined, as did the rule that women had to leave when they became pregnant. The rule about leaving when you married had already gone. "All those hurdles have been knocked down now. We actively encourage everyone to stay because of all the experience that they have gained throughout their careers."

Gray is keen to encourage more young women into a role in engineering © RAF

As well as changing its approach to recruiting and retaining people, Gray has seen big changes in the RAF's engineering needs. Like many organisations, the air force has become increasingly dependent on information and communications technologies. "We were quite good at reshaping bits of metal," she says, but it is now much more about systems engineering. "Every aircraft is controlled by a computer really," she adds. "You can set the computer to do certain things but ultimately if it says 'no', you're not going anywhere." The RAF's engineers need training to develop those skills, so many were upskilled in systems and software engineering.

As Gray sees it, for the RAF the next generation is about systems engineering, cyberspace and data, understanding how to use it, and using it securely. "Using data securely is key because we rely upon being one step ahead." The good news is that Gray is optimistic about the young people who are likely to follow in her footsteps. "Most young people I come across that are interested in being engineers are technically minded, innovative and enthusiastic – a great combination."

As for her own priorities, Gray says: "I am pretty much focused on the next generation and what we can do from a technical perspective. It is about enthusing the next generation, and giving them the confidence and skills to be able to be innovative; without that there won't be a future."

BIOGRAPHY

Michael Kenward OBE has been a freelance writer since 1990 and is a member of the *Ingenia* Editorial Board. He is Editor-at-Large of *Science|Business*.

CAREER TIMELINE AND DISTINCTIONS

Born, **1963**. Studied physics and electronics at Newcastle Polytechnic, **1985**. Completed a master's in aerospace vehicle design at Cranfield University, **1994**. Appointed Officer of the Order of the British Empire, **2005**. Became Air Vice Marshal, **2014**. Appointed Air Officer Commanding No. 38 Group, **2016**. Appointed Companion of the Order of the Bath, **2017**. Fellow of the Royal Academy of Engineering, **2018**. Appointed UK's first female three-star officer, **2019.**

ROBOTS IN THE FIELD

Four years ago, three engineers began developing a robot designed to autonomously pick and sort strawberries. Three designs later, the first group of 24 robots is reaching UK fields this summer. The robots will navigate the crops and select ripe fruit, before picking, inspecting and packing the strawberries.

In June 2015, the three founders of Dogtooth Technologies decided to start working on an innovation that would have an impact in the real world. With its large revenues and small margins, the agricultural industry appealed to them and they believed that there was real scope to increase productivity and decrease waste. In 2018, almost 60% of agricultural businesses experienced a shortage of workers, leaving crops unpicked. Robot workers could be the solution. After exploring dozens of ways of using computer vision in the sector, they decided that a robotic system to pick strawberries could add the most value per metres moved or unit of time.

The founders all have backgrounds in software engineering and computer vision, and the project has involved engineers from most major disciplines: mechanical, electronic, software, and firmware engineers have all contributed. Dogtooth designs and manufactures its own robot arms and cameras, and the system's machine-learning and computer vision software is bespoke. The company developed a few prototypes, four of which have been working in the field for 18 months in the UK and Australia. Now the robots are ready to get to work on a wider scale. They are designed to work on the same farms as human pickers using existing infrastructure.

A 3D camera system mounted to the robot arms surveys a row of strawberries to detect a single strawberry and locate it. The robot arm moves in to inspect the strawberry and decide whether it is ready for picking. The device uses machine learning to detect ripeness based on the colour of the fruit, before considering other factors, such as whether it can be picked without damaging nearby fruit and whether the arm needs reconfiguring to pick it. Once the robot has decided to pick the fruit, the robot arm snips the strawberry's stalk just above the leaves, never touching the strawberry itself.

Strawberry-picking robots will help fill staff shortages, preventing food waste and making farming more productive © Dogtooth Technologies

After the strawberry has been picked, it goes through a quality control step where the robot reviews the fruit under controlled lighting and inspects it for 17 types of defect, such as bruising or mould. It also measures its mass and checks for ridges and asymmetry, before sorting the strawberry into different punnets based on quality. The picker also ensures that punnets have the correct weight of fruit in them, whereas when strawberries are picked by people the punnets are normally sorted later to ensure that they weigh the right amount. The robots work at approximately half the speed of a person, but can work for twice as many hours and save time on sorting and packing.

One of the key challenges was the control software for the arm. Dogtooth needed to optimise route-finding, which is very different to traditional robotics – for example, robots that build cars follow set routes repeatedly, whereas Dogtooth's robots are constantly observing and making decisions about what to do next. The camera can ask the arm to move anywhere within the robot's reach, so it needed to be programmed to ensure that it did not crash into itself or plants and to move efficiently. The robot is always learning and collects data (about yield for example), labels data and trains algorithms. The strawberries can be traced from flower to the packing house, and the company collects data on strawberries every two days for nine months of the year.

This summer, 24 strawberry-picking robots will be picking fruit in the UK before spending winter in California and Australia. Then, Dogtooth will begin work on robots that pick other soft fruits, such as raspberries.

For more information, visit **https://dogtooth.tech**

HOW DOES THAT WORK?
BEAMFORMING

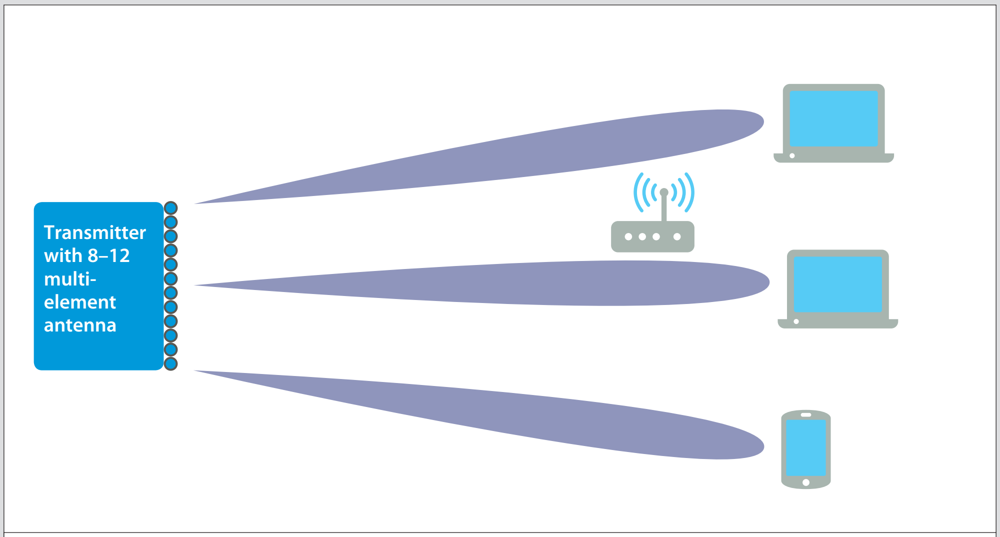
The next generation of cellular technology, 5G, is said to have 'beamforming antennas'. What are these and why do they help?

Broadly, today's 4G technology could be likened to having a lightbulb illuminating a whole room (or in some cases one-third of a room in a pie-shaped 'sector'). Tomorrow's 5G technology will focus the radio energy towards the handset in a narrow beam more like a searchlight.

This has two key advantages. First, focusing the energy means that it goes further, much as a torch can cast a beam further than a lamp, enabling greater range from base stations. Second, if there are multiple beams formed within a cell, and if these are not overlapping, then the same radio frequencies can be used for each beam, but with each one sending different information pertinent to their subscriber (the person using the device). The number of beams then increases the capacity of the cell.

Beamforming antennas do not use a lens as these are both difficult to make for radio systems and hard to steer mechanically towards the subscriber. Instead, they make use of a large number of elements, or mini antennas, within a larger structure. Antennas proposed for 5G base stations have 64 or 128 small antennas within them. A beam is then formed by taking several of these elements for one subscriber (say four or eight) and sending the same signal to each element but delaying the signal to some of the elements. This has the effect of steering the beam as shown right.

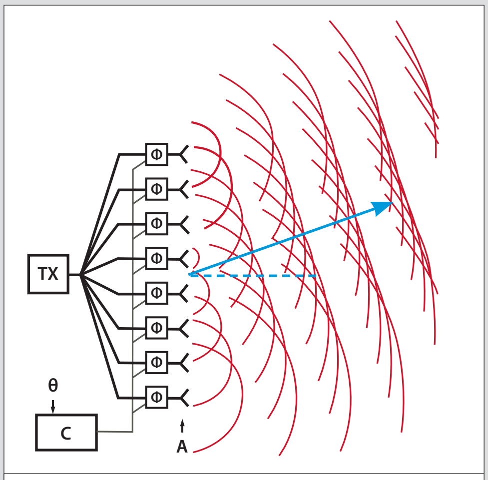
To understand intuitively how the beam is steered, think of each antenna as transmitting a wave of radio energy. At the receiver, all these waves add up together in the antenna. If just two antennas were used, in some places their signal would be in phase so that the peaks in the wave arrived simultaneously. Here the receiver would see a strong signal. At other places, they would be precisely out of phase so that the peak of one wave arrived along with the trough of the other. Here the signals would cancel and the receiver would see nothing. A receiver that was not directly perpendicular to the antenna would be further from one antenna than the other, so by delaying the signal to the closest antenna by the time that corresponds to this distance then a strong signal will be received. Two antennas would give rise to a whole series of these strong and weak areas. However, as more antennas are used the number of these areas reduces, resulting in a progressively narrower beam, which forms alongside the main beam as a function of the number of signals combined and their relative delays.



This diagram demonstrates how narrow beams can send different information to multiple subscribers

A different subscriber is then assigned another set of elements where different delays are used to steer that beam in a different direction.

There are many trade-offs. The more elements used per subscriber, the more focused the beam is and less focused the unwanted 'mini-beams' created around the main beam. However, where there are more elements, the larger and more expensive the base station antenna becomes. Also, as the beam becomes narrower, it becomes harder to keep it perfectly aligned on the subscriber, especially if they are fast moving.



Changing the phase of the signal causes a beam to be formed in a particular direction

These ideas of forming beams by phasing signals to discrete antennas are far from new: radar and sonar systems have used them for years. However, this will be the first time that they will be applied to mass-market cellular systems.

Investing in the
next generation
From world-class engineers to brilliant data scientists, the next generation of talent really matters.
We develop our employees’ skills and potential to the full, including high-quality training for over 2,000 apprentices and graduates across the UK.
Because investing in their future is critical for ours.
Commitment where it counts.
baesystems.com/ukcareers
Copyright © 2019 BAE Systems
BAE SYSTEMS

Coal Drops Yard, London
© Hufton+Crow/Arup