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JUNE 2020 ISSUE 83

HARNESSING OCEAN ENERGY
ENGINEERING IN A CRISIS
ROBOTIC SURGERY
FLOODING A STAGE
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Lithium-ion batteries © WMG

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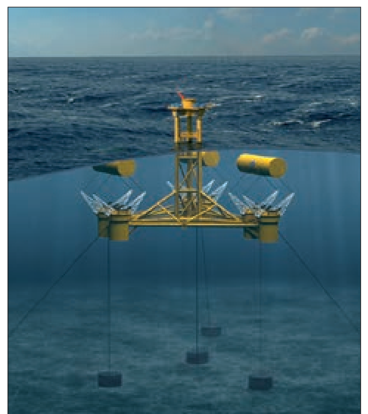

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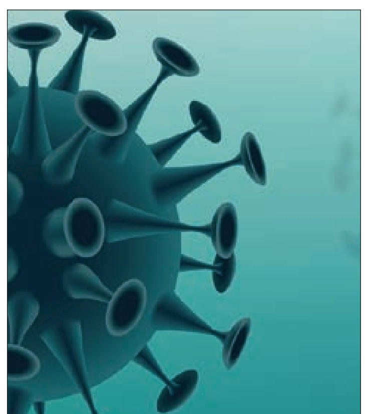

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EDITORIAL

TIME TO CHEER FOR INDUSTRY

Scott Steedman CBE FREng

As the coronavirus COVID-19 spread around the globe and cases mounted in the UK, many hoped that this would be a transient crisis and that life would return to normal. It has become very clear that we are a long way from any sort of normal. The question for industry, and for the country, is whether this is a new era, not just a new normal.

As the global pandemic broke, engineers in industry and academia responded to a shortage of ventilators and personal protective equipment (PPE) with speed and agility. Suddenly everyone was talking about PPE, an essential clinical need that, like manufacturing, we had previously taken for granted. The breakdown in global supply chains forced the government rapidly to rethink established processes for procurement and regulatory approvals. For their part, manufacturers quickly adapted production lines to meet new demand through both re-engineering old products and innovation.

The immediate crisis may be receding but there are many lessons to be learned. The nation is still in a fragile state. Despite heroic efforts to support the country, the nationwide shutdown has left companies facing a dire future as they struggle to restart operations. The nation clapped for the NHS, now it must cheer for industry, for critical infrastructure workers, for financial services, for everyone going to work to rebuild the economy. Without a concerted effort to champion safe working guidelines that help us get back to work, reoccupy facilities and rebuild broken supply chains, UK industry will lose out in the global market as other countries exit lockdown and resume business.

Beyond recovery lies renewal. Will the world after COVID-19 see a new understanding, a coming together of nations determined to shape their economic renewal in a different way to the past? Globalisation based on minimum cost and token attempts at sustainable development, already under question before the pandemic, has gone. In its place there should be an international consensus that global crises need global solutions. The UK is well positioned to play a leading role in this rethink. As one of the most innovative countries, our science and engineering can underpin national renewal.

We must resist any temptation to use the pandemic as an excuse to cut investment to recoup the cost of lockdown. Instead, we need to accelerate investment in infrastructure, telecommunications, energy, and high-speed rail. We must tackle the productivity gap with massive deployment of digital technologies, supported by full-fibre broadband, across the UK. Only then can we mobilise our human capital effectively.

Digital home-based employment works for some, but the COVID-19 crisis has forced industry into a 'new normal' for which it was largely unprepared. It will take a nationwide programme of training and skills development, for employees and employers, if we are to learn to use the online workplace effectively. Virtual meeting platforms have provided some continuity for business but cannot be an adequate long-term solution. Already the UK's online gaming industry is adapting its world-leading software skills to support employers as they switch to the new ways of working.

Supply chain resilience, operational resilience and information resilience will be key to industrial success after COVID-19. UK engineering companies need to develop trusted, diverse supply chains, secure digital platforms, and a flexible and connected workforce. We need to 'Build Back Better', build back green and lead the drive for net zero carbon emissions in our own operations and across every supply chain.

National renewal must put engineers and engineering at the heart of any future industrial strategy. No longer should we treat manufacturing as an unloved, aged relative, but as an integral part of the future economy. Empowering people to participate in the new global market for products and services will require completing the transition to an information economy, connecting people to companies. Bringing innovative 'factory in a box' solutions to towns and shopping centres, tying together flexible manufacturing and information technologies, could unlock local creativity and build on the volunteer spirit seen throughout lockdown.

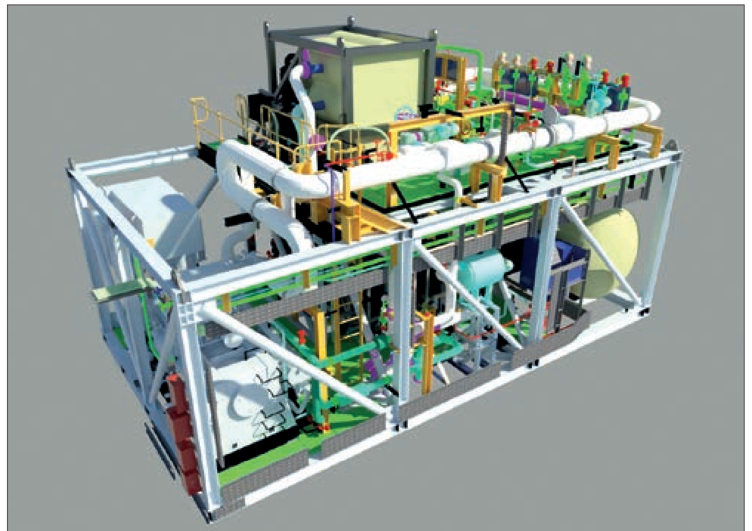
We thanked healthcare workers for their extraordinary commitment in our national time of need. Now we need to cheer for industry and for economic recovery and renewal.

Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

IN BRIEF

MACROBERT AWARD FINALISTS FOCUS ON SUSTAINABILITY


A computer rendering of Babcock's ecoSMRT® system for transporting liquified natural gas © Babcock's Liquid Gas Equipment

Jaguar Land Rover's I-PACE – the world's first battery-electric sports utility vehicle © Jaguar Land Rover

The innovative fully electric digger, 19C-1E, developed by JCB © JCB

Jaguar Land Rover, JCB and Babcock's Liquid Gas Equipment (LGE) business have been announced as finalists for the 2020 MacRobert Award, representing world firsts in UK engineering that are contributing to a low-carbon revolution in motoring, construction and shipping.

As the most prestigious prize for UK engineering innovation, the MacRobert Award shortlist recognises engineering innovations developed in the UK that deliver tangible social benefits through significantly reduced environmental impact. These finalists are all British teams that are reducing vehicle emissions, from construction and shipping to family cars.

Based in Fife, Scotland, Babcock's LGE business developed ecoSMRT®, which has dramatically improved the efficiency of transporting liquefied natural gas (LNG). Ships carrying LNG must control the pressure of their LNG cargo, as evaporation occurs in the tanks. The ecoSMRT® system captures and reliquefies this 'boil-off' gas, with significant reductions in emissions compared with current technology. It delivers up to a 50% reduction in carbon footprint, a 50% reduction in maintenance costs, 40% reduction in the physical space required, and improves power efficiency by up to 20% when compared with existing systems. Each ecoSMRT® reliquefaction system in service on an LNG ship will save the equivalent of up to 19,000 tonnes of CO_2 from being emitted per year.

Jaguar Land Rover has been nominated for I-PACE, the world's first battery-electric sports utility vehicle (SUV). Jaguar Land Rover is one of the first major vehicle manufacturers to transition to electric vehicles. Its design, engineering and technical specifications mean that the I-PACE has a range of up to 292 miles. Its core innovations include novel approaches to battery, thermal management and e-motor technology. The I-PACE was granted 40 significant patents for its innovative technology overall.

JCB has developed and manufactured the world's first volume-produced fully electric digger (19C-1E), with zero exhaust emissions, improved productivity, noise and vibration characteristics, and emission-free for use inside buildings. Rapid urbanisation is happening across the globe, but this is negatively impacting air quality and global warming initiatives. The JCB 19C-1E is the only volume-produced, battery-powered excavator on the market. To date, the current fleet has saved the equivalent of 15,100 kilograms in CO_2 emissions across 5,616 hours of work.

The winner will be announced in July. The winning team will receive the MacRobert Award gold medal and a £50,000 cash prize.

The MacRobert Award is run by the Royal Academy of Engineering. Since 1969, it has recognised engineering achievements that demonstrate outstanding innovation, tangible societal benefit and proven commercial success.

ENGINEERING EVENTS MOVE ONLINE

The Royal Academy of Engineering has launched an online events programme so that audiences can continue to learn about engineering innovation, ranging from the response to the COVID-19 pandemic to space technologies.

Online events have already included a collaboration with Edinburgh Science Festival to bring it online, which featured a talk from Dr Dame Sue Ion DBE FREng FRS titled *Energising engineering: half a century of British innovation*. The annual Royal Academy of Engineering/Royal Society of Edinburgh joint lecture also took place virtually, on the topic of bringing space down to Earth, where a panel of experts discussed how space technology is used and Scotland's role in developing the space technologies of the future.

The Academy is also hosting an online Q&A series, *Innovation in a crisis*, to explore the different ways that the engineering profession is contributing to the COVID-19 response. So far, the series has explored the engineering behind the Nightingale hospitals and the VentilatorChallengeUK.

Visit **www.raeng.org.uk/events** for upcoming event information.

GOLDFISH GREENS AND MECHANICAL CLOCKS

Two young students have won the Big Bang Competition's young scientist and young engineer of the year awards.

Diya Vincent, a Year 7 student from Sevenoaks School in Kent, was named the GSK UK Young Scientist of the Year title for her project titled 'Microgreens from Goldfish', which grew microgreens using fertilised water from an aquarium and then compared them using three different methods.

Chris Kalogroulis, aged 18, won the GSK UK Young Engineer of the Year award for his project, Flip. He created a sustainable and minimalist mechanical clock, which he wanted to have aesthetic appeal as well as allowing him to learn and apply mechanics, electronics and programming. Chris is currently in his first year at Imperial College London studying design engineering.

The Big Bang Competition recognises and rewards young people's achievements in all areas of STEM, while providing them with the opportunity to build their skills and confidence in project-based work. The competition is open to all UK residents in full-time education or training.


Diya Vincent (left) and Chris Kalogroulis with their winning designs

IN BRIEF

SYSTEMS FOR SUSTAINABLE HOUSING

The map that was created from the findings of the *Developing a systemic perspective for sustainable living places* report

In early June, the National Engineering Policy Centre launched its sustainable living places report, *Developing a systemic perspective for sustainable living places*.

The report focuses on applying systems thinking to housing in the UK and the wider system in which it is situated, applying an approach that is appropriate for tackling complex policy issues that have a social-technical dimension. The systems methodology and approach led to a map, findings that show where activities in one part of the system may influence other parts of the system, and an illustration that brings these themes to life. The findings raise issues specific to the planning of housing, place and infrastructure, and discuss the strengths and challenges of applying this systems approach.

The report's findings are aimed primarily at the Infrastructure and Projects Authority, which commissioned this piece of work. It will also appeal to an audience interested in testing applications of systems approaches connected to the delivery of places. Other audiences of interest include policymakers in government working on housing, professional engineering institutions and infrastructure stakeholders interested in exploring an application of a systems approach.

The National Engineering Policy Centre is an ambitious partnership, led by the Royal Academy of Engineering, between 43 different UK engineering organisations representing 450,000 engineers.

STEM AT HOME

The Royal Academy of Engineering has launched a competition encouraging students to show off their creativity, imagination and problem-solving skills by taking part in STEM activities at home.

Engineers in the Making sets a new challenge every two weeks, asking students to send in photos or a short video along with one or two sentences to explain their innovation. Previous challenges have included building a vertical farm at home and making pop rockets. The best entries can choose from a selection of prizes including a power and play K'Nex set or a robot to build and programme. The competition is open to school children aged 7 to 14, across the UK. To enter the competition, visit **www.raeng.org.uk/engineers-in-the-making**

The competition is part of the Academy's STEM at home response to the closure of schools across the UK. It has given parents and teachers access to several easy and fun education resources to help children learn at home.

The STEM resources support children's home learning through practical, hands-on activities that encourage tinkering, investigation, problem finding, and solving real-life engineering challenges. All activities use items found in the home, such as a torch, scissors, glue, cornflour, paper, cardboard, and other recycled material, and have simple-to-follow instructions.

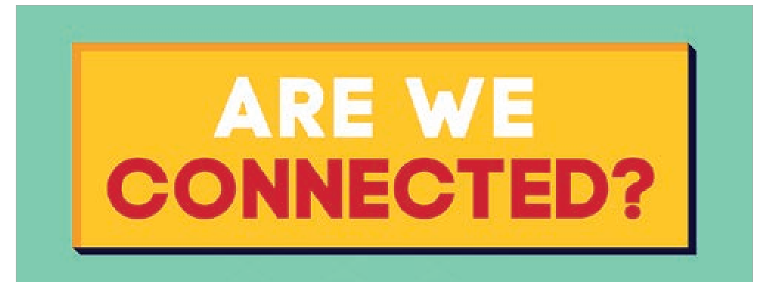
The activities allow students to get stuck in, make mistakes, ask questions, build, design, experiment, and have fun. To access the resources below, as well as many more, please visit **www.raeng.org.uk/stem-at-home**

GREAT EXHIBITION AT HOME

This resource is inspired by the original Great Exhibition of 1851 and asks young people to explore how engineers can help protect the planet. Weekly activities, digital resources and a video challenge for participants build up to a final video challenge that asks students to create and share a 'Great Exhibition', wherever their classroom may be. Highlights so far have included compost-powered energy, a magnetic-fuelled wind turbine and a cushion for cars to stop killing the endangered Florida panther, which is the largest human cause of the species' death.

POWER UP!

This resource is focused on energy and engineering careers in that area. Power up! looks at the importance of electricity, how it is generated and global electricity consumption, and investigates different forms of energy and types of renewable energy sources through hands-on practical activities. This includes: creating a circuit to investigate energy transfers using different objects that can be found around the house; designing and building a Rube Goldberg machine; and building a mini wind turbine using recycled material.



ARE WE CONNECTED?

This resource explores engineering through the technology we communicate and connect with. Enquiring and practical activities teach about the electromagnetic spectrum; 'find your friends' on a map of the UK and Ireland using trilateration; consider the ethics around artificially intelligent technology; use algorithms to build shapes using tangrams; program a virtual Sphero ball; and use code-breaking skills to decrypt text.

LIGHT SAVER

This resource investigates how properties of light have been used to develop a new light-based technique to help diagnose and monitor the health of babies' brains. It looks at the visible light spectrum, nanometres, behaviour of light, and health monitoring. Students can use an interactive tool to compare light waves and investigate how light behaves, interacts with our bodies and is used in medical engineering through several experiments that just need a torch, water, food colouring, and gummy bears.

IN BRIEF

IN BRIEF EXTRA

ABANDONED TUBE STATION HELPS HEAT HOMES

In a world first, hot air extracted from London Underground's Northern line is being used to generate warm water to heat homes, a school and two local leisure centres in Islington. Opened in March 2020, Bunhill 2 Energy Centre, a project led by Islington Council, is helping reduce residents' energy bills, cutting carbon emissions and providing electricity for neighbouring amenities.

The two-metre wide fan at the unused City Road station sucks up hot air via a ventilation shaft and can be reversed during the summer to provide cool air to the Underground © Transport for London

HEAT FROM BELOW

District heating networks are being increasingly used to deliver cost-effective low-carbon heat, using any heat source of sufficient temperature to provide heating. There are many urban infrastructures that could supply waste heat including sewage works, electric substations, data centres, and rail tunnels.

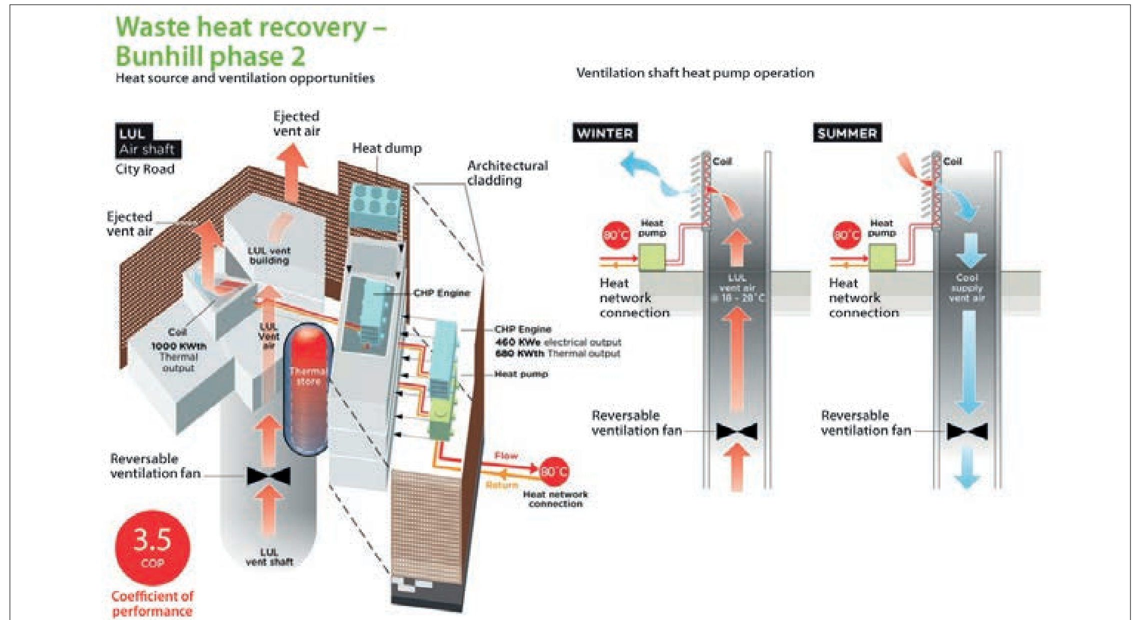
The location for this district heating network is the abandoned City Road Tube station – between Old Street and Angel. Derelict since 1922, its old lift shaft has been used as a ventilation shaft for decades. Now, a two-metre wide reversible fan extracts Tube tunnel air up the six-storey vertical passage, over a set of coils to heat pumps that convert the waste heat into hot water for 1,350 homes.

Train braking friction between rails and wheels, as well as passenger warmth, cause the Underground to become warm. The London Clay soil that surrounds most of London's Tube tunnel walls acts as an insulator, resulting in air temperatures in this shaft reaching a minimum of 18°C in the winter and a maximum of 28°C in the summer.

Ramboll, the client engineer commissioned by Islington Council to develop the design of Bunhill 2, has helped create an energy centre that draws the underground air to a heat-exchange system positioned at ground level, 23 metres above the Tube. The air passes over a coil unit of water-filled pipes heating them by around 5°C. The water temperature is then increased further using a two-stage process.

A heat pump, powered by electricity generated from two gas-powered CHPs (combined heat and power engines), raises the water heat. Then the thermal output from the CHPs heats the water further until it reaches 80°C when it is ready for distribution. A pair of parallel insulated pipes in a closed-loop communal heating system carry the water underneath the streets to and from the destinations – hot one way, cool to return.

Islington's Bunhill Heat and Power Network consists of Bunhill 1, launched in 2012, and Bunhill 2. The two power centres are fully integrated and operate in parallel to generate and inject heat into a single shared network.



Schematics showing Bunhill 2's operating system. At Bunhill 2, the heat pump operates as primary plant to raise temperatures up to 70°C, using two-stage reciprocating compressors (also known as 'pistons') to achieve an annual coefficient of performance (COP) – or heat pump efficiency – of 3.5 (indicating the generation of 3.5 kilowatts of low-carbon heat for every 1 kilowatt of electrical energy consumed) © Ramboll

Bunhill 1 is powered by a single two-megawatt CHP engine and is paired with a 115-cubic-metre thermal storage tank that supplies heat to nearly 800 homes. Bunhill 2's new pipework adds a further 550 homes and a primary school and enlarges the potential capacity to a combined total of 2,200 homes. Both centres produce surplus electricity, which is sold back to the National Grid.

NET ZERO

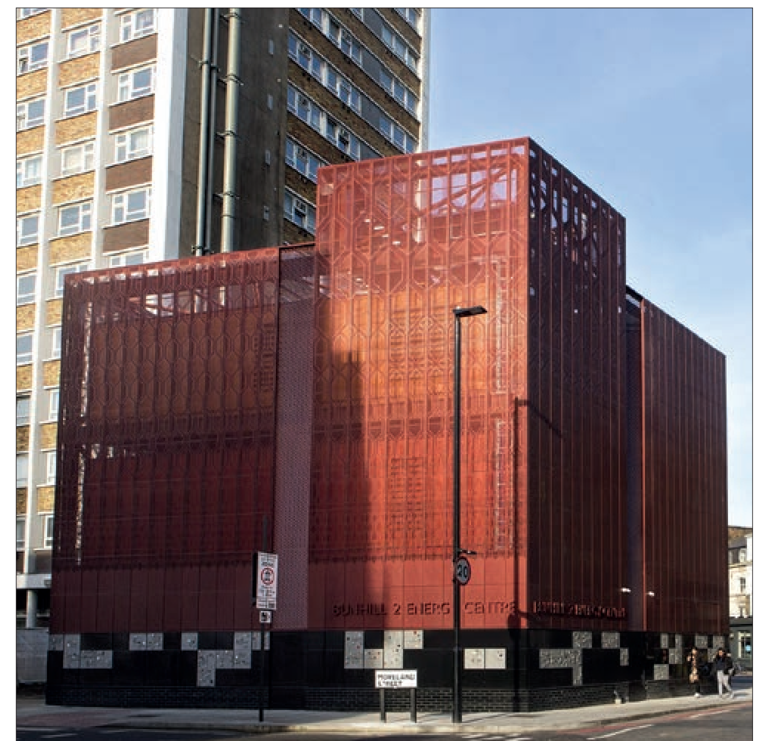
The £16 million project underlines the council's commitment to be a net zero carbon borough by 2030. Bunhill 2 has reduced heating bills for council tenants connected to the network by 10% compared to other communal heating systems, which themselves cost around half as much as standalone systems heating individual homes.

In the UK, heat networks supply around 2% of heating demands. The 2017 London Environment Strategy set a target for the capital of achieving 15% through district heating networks and renewable energy supplies by 2030.

Transport for London intends to follow up its input into Bunhill and has studied 56 ventilation shafts to assess the potential of each for exporting waste heat. Detailed technical feasibility studies have been completed for six selected sites and plans for development will be announced by the end of 2020.

Islington Council is also looking to expand its district heating network capacity by exploiting other waste heat sources. These include an underground electrical substation; a water source heat pump in Regent's Canal, which runs through the borough; and a local data centre, with a heat pump providing cooling to the centre and heat to the network; and by using boreholes as storage.

Capturing urban waste heat – heat that would otherwise be lost – on a localised basis is catching on. There are many examples in Denmark, including dozens of supermarkets that are being retrofitted to generate heat from their cooling systems. In Germany, the thermal potential of sump water from open pit lignite mining is being used to supply heat to nearby communities. Meanwhile in Finland, a large data centre has a heat pump that converts its hot air to a heating network supplying 1,500 homes.



Cullinan Studio designed the dark copper-coloured building that houses the Bunhill 2 energy centre. The outside structure encloses the three shipping containers that store the plant and machinery and can be replaced when needed. The façade's removeable aluminium panels have perforations that increase in size as they go up, to enable greater ventilation for the units at the very top © Islington Council

Words: Dominic Joyeux

HOW I GOT HERE

HOW I GOT HERE

Q&A

ROSIE GOLDRICK
STRUCTURAL ENGINEER

Rosie Goldrick

Rosie Goldrick is Engineering Director at MASS Design Group, a non-profit design collective that builds and designs innovative projects throughout East Africa, with a focus on education, health and justice.

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

I grew up in London, surrounded by historic buildings and skyscrapers as well as rundown housing estates, so I always understood the impact of the built environment on how people live, work and travel. That was when I first became interested in designing buildings. My aunt was an architect, and I was quite good at art and maths, so initially I was leaning towards architecture. However, I had a really good careers advisor who told me about structural engineering.

HOW DID YOU GET TO WHERE YOU ARE NOW?

Before I started university, I did a year in industry with Mott MacDonald. I also received the Institution of Civil Engineers' QUEST scholarship, so was sponsored by Atkins at university. I would work there every summer, and work for Mott MacDonald every Easter, both of which gave me valuable real-life experience while I was studying. I studied civil engineering and architecture at the University of Southampton.

After university I worked for Atkins for five years, mainly designing big infrastructure. One of the best projects I worked on there was the Doha Metro underground stations, where we designed the 13 stations on the Gold line. I was lucky to be able to work in India for this project, as the design was being worked on from Scotland, India and Qatar.

In 2016, I took a one-year engineering placement with Engineers Without Borders in Rwanda with MASS Design Group, and never left.

WHAT HAVE BEEN YOUR BIGGEST ACHIEVEMENTS TO DATE?

My proudest achievement is expanding the engineering team here – we've grown from just four people to 22 and are now a group of multidisciplinary engineers. It's great to be working in a team with broad mix of nationalities and specialties: architects, landscape architects, engineers (structural, geotechnical, MEP and civil), product designers, and constructors. We have such a focus on training and keeping staff that we've developed a reputation in the industry here for being good for training, and that's been really rewarding. Four years ago, our engineering team was just three people and not well known, but now we get so many CVs from people who want to work here.

Last year I also received a Royal Academy of Engineering Engineers Trust Young Engineer of the Year award, as well as the Sir George Macfarlane Medal. It was nice to get that recognition and one of my colleagues had nominated me so that was a huge personal achievement.

WHAT'S YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

I love figuring things out and solving problems. The nature of the work requires a good understanding of maths and physics, but it's really creative too, which I think people don't always realise. There's a lot of collaboration and creativity involved in solving complex problems, and I love working with a range of disciplines. We have to be able to work with everyone to explain and defend our designs, and use

Rosie and Shakira load testing a timber beam with buckets of stone

judgement in balancing different factors such as safety, durability, cost, sustainability, and user experience.

I also love that I get to work in the office and on site, where I spend about one day a week. It's great to see something that you've drawn on paper come to life. The first time I saw something I designed get built was a great achievement. In my old firm, we worked on huge infrastructure projects that ran for five or ten years, so I didn't really get to see things from start to finish.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

At the moment we're working on an agricultural university campus, the Rwanda Institute for Conservation Agriculture (RICA). This project includes student housing, faculty housing, and different teaching buildings. We're also working on a purpose-built gorilla conservation facility, the Ellen DeGeneres Campus of the Dian Fossey Gorilla Fund, to help them to protect and study gorillas, train the next generation of African conservationists, and build the conservation capacity of local communities.

When I'm not on site, I'm usually managing projects in the office, carrying out structural design and coordinating with the architects. I am also responsible for the management of the team, so I spend some time figuring out their workload and who will work on what.

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

Engineering is a great career choice. It's really creative and there are so many diverse opportunities. My advice would be try and do some work placements to get a sense of what you enjoy because there are a lot of different routes into engineering and so many disciplines. Placements could be site-based or office-based or a bit of both, but it's good to get experience. Before choosing civil engineering, I did some mechanical engineering work placements.

WHAT'S NEXT FOR YOU?

I think I'll be here in Rwanda for the foreseeable future. I hope that my focus can be on utilising local materials and efficient low-carbon design in response to the climate crisis. Using local materials also helps to boost the local economy. My other main focus area is seismic design; structural engineering plays such an important role in safety, so we do quite a lot of advocacy work on designing and constructing safely with low-carbon materials. It would be great to continue to have buildings that exemplify that, which we can use as examples to show that it really can be done. RICA, the agricultural university that we're working on, has just 40% of the embodied carbon of the global average – it shows people that it can be done in Rwanda, not just Europe or the US.

QUICK-FIRE FACTS

Age: **32**

Qualifications: **MEng, CEng.**

Biggest engineering inspiration: **When I was young I was very inspired by the various bridges across the Thames.**

Most-used technology: **Slack, Autodesk® Robot™.**

Three words that describe you: **empathetic, energetic, extroverted.**

OPINION

OPINION

NET ZERO – ASPIRATION OR REALITY?

Food is one example where the challenges are greatest. On average, it currently takes roughly ten calories of fossil fuel to put a calorie of protein on a person's plate. Food production probably needs to be five to ten times more energy efficient by 2050 than it is today

Professor Sir Ian L Boyd FRSE

When the UK government legislated in 2019 for net zero carbon emissions by 2050 there was close to unanimous support. It is easy to sign up to goals that are both aspirational and sufficiently distant so that accountability for reaching them will lie with others. This is no different to the idea that irreversible resource depletion in the present will be a problem that future generations will have to solve because we cannot, or cannot be bothered, to solve it in the present.

There are ethical and moral principles at stake here. Much of engineering, and also science, is stimulated by the need to do good things where the outcome of our work brings greater overall benefit than if it had not happened – in other words, greater utility.

This view of an ethical framework for action is challenged by the difficulty of assessing what will be good in future. Was the invention of the internal combustion engine good in retrospect when it has been one of the drivers of climate change? Are pesticides good inventions because they increase crop yield although, as we come to understand their diffuse actions in the environment, they can have negative impacts as well?

Consequently, even if we are clear about the positive results from achieving net zero greenhouse gas emissions, are all the things that we are doing now going to genuinely contribute to this objective, or do they just serve short-term interests? Are they actions that are cloaked in rhetoric about their contribution to the net zero objective while their real purpose is to underpin business as usual?

The Committee on Climate Change has set out actions that are needed to meet net zero. Although its analysis seems sound, the explanations are fuzzy. The true impact of the analysis has been lost in the committee's simple message that it is possible to do what is required through some tweaks here and there to business as usual. I think this is profoundly wrong.

We need to go through an energy transition equivalent to the historical transitions from wood to coal, and then from coal to oil. The transition from oil to nuclear has notably failed. While we are not quite at a standing start when transitioning to non-renewable sources of energy, we need to make the transition in one human generation, or a shorter time than the lifecycle duration for major infrastructure.

I guess this is just about possible – the market can do amazing things when it is set appropriate goals – but it is impossible when the price of carbon is as low as \$20 to \$30 a tonne, as it is now. The market currently operates using agreed rules, which need to be reconstructed. Governments need to take a unified position both nationally and internationally. Unfortunately, there is no clear sign this is going to happen soon.

If the supply side is challenging, the demand side is even more difficult. The transitions that need to happen here involve highly dispersed systems – electricity grids, domestic heating and power, transport and food production. Some of these are easier to transition quickly – for example in transport, personal vehicles could be switched swiftly – but the lifecycles for many other systems last many decades, and even centuries.

Food is one example where the challenges are greatest. On average, it currently takes roughly ten calories of fossil fuel to put a calorie of protein on a person's plate. Food production probably needs to be five to ten times more energy efficient by 2050 than it is today.

Such a transition needs simultaneous supply- and demand-side transformation. The engineering challenges on the supply side will involve controlled system farming (so called 'vertical farms') and other kinds of technologies. For example, coastal desert regions where there is plentiful solar energy, fresh water from seawater desalination and cheap land are likely to provide opportunities for culturing food in ways that give the kind of efficiencies needed.

Changing the demand side will require the environmental costs of current food production to be reflected in the price of food. Whatever people actually say about their reasons for buying certain foods, they are most influenced by price and most people eat processed foods of some sort. Changing demand is not, therefore, as difficult as might be imagined. However, these changes will mean sacrificing parts of the traditional farming industry and its methods, including much of current meat and dairy production.

If, by 2050, we could make every aspect of our food production as good as the best-in-class today we will have solved the problem. But this will require investment in the engineering needed to do this at scale, alongside development of the policies needed to shift demand.

Have we got the determination to make this and other similar efficiency transitions happen? COVID-19 should be a wake-up call. Although it is not linked to climate change *per se*, it is linked to the kind of lifestyles that have generated the problem of climate change. We will see some people calling for climate actions to be ditched in order to get back to business as usual as quickly as possible. This is precisely the wrong way to go. If the COVID-19 tragedy is going to have a lasting positive legacy it should be to help us understand our vulnerabilities. It is the opportunity to press reset by setting enlightened rules about how development and regrowth might happen.

BIOGRAPHY

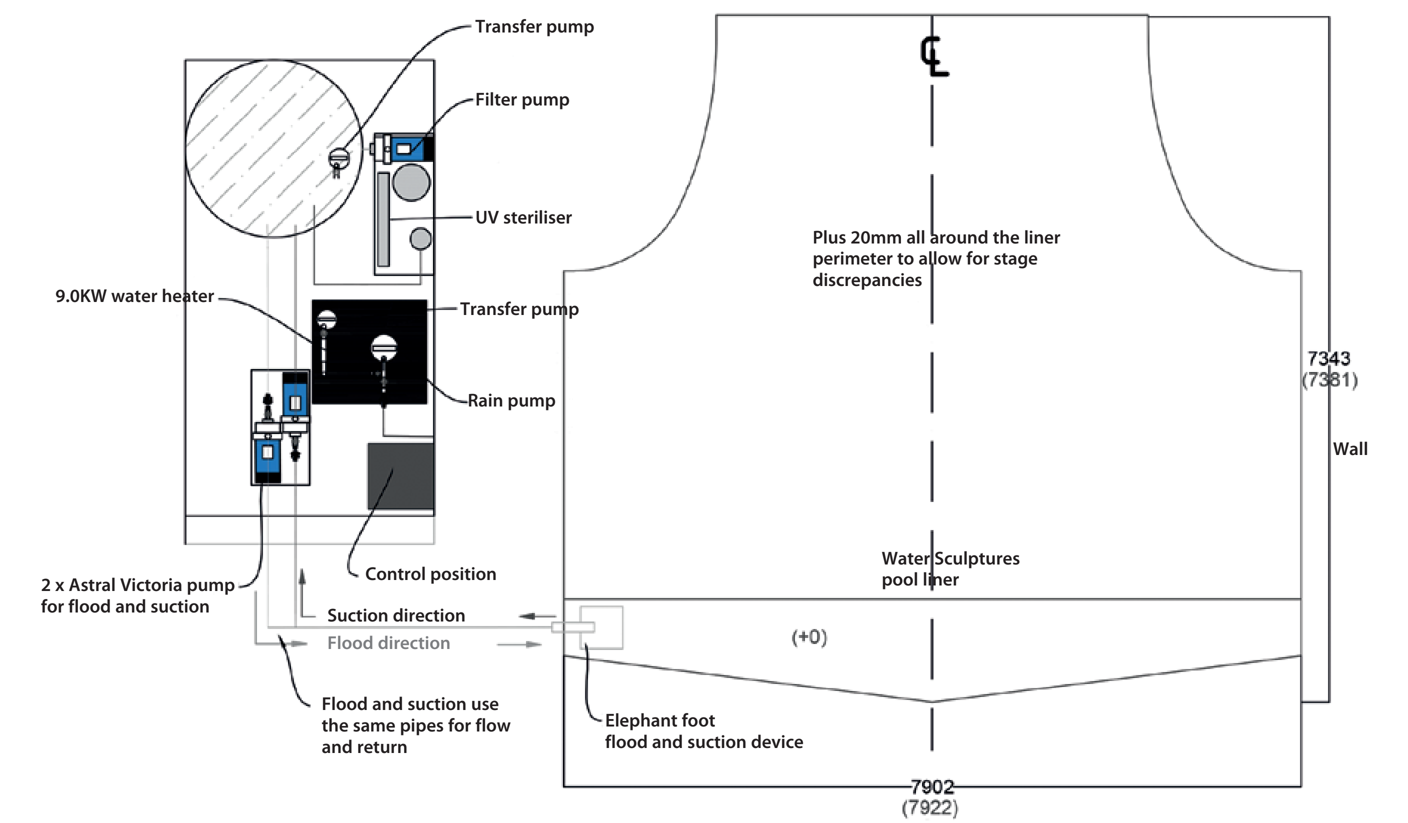
Professor Sir Ian Boyd FRSE is a professor in biology at the University of St Andrews. He was previously Chief Scientific Adviser at the Department for Environment, Food and Rural Affairs from September 2012 to August 2019.

MAKING IT RAIN

The closing number of *Singin' in the Rain*. All the dancers, apart from the front two, are dancing on flooded boards within a 'pool' area. The falling rain and flooded tank below the stage allow the cast to splash in two-centimetre-deep puddles © Jonathan Church Productions

A hugely successful stage production of *Singin' in the Rain* is due to relaunch at Sadler's Wells Theatre in 2021, before going on a worldwide tour. The show's highlights are two dance sequences in the rain, which posed logistical problems for its designers. Dominic Joyeux talked to theatre designer Simon Higlett and William Elliot, Technical Director at Water Sculptures, about the challenges of flooding the stage.

Water Sculptures flood and suction system | *Singin' in the Rain* 2020



Plan view of the onstage flood and suction system, integrated water storage system and heated rain container, looking from the front of the stage. The system is located in the wings, approximately 15 metres away from the performance area. © Water Sculptures Ltd

When theatre designer Simon Higlett was asked to create the set for Chichester Theatre's 2011 production of *Singin' in the Rain* he was enthusiastic but wary: inundating a stage with water can cause problems, from ensuring equipment stays dry and avoiding technical problems to making sure performers are comfortable and actually getting the water on stage. Technical issues had previously meant that a river built at the National Theatre's Lyttelton stage for Alan Aykbourn's play *Way Upstream* burst its banks and flooded the theatre, causing performances to be cancelled. *The Times* reviewed it with the headline 'Up River without a Paddle'.

Simon's main concern was how to deal with the presence of water on stage. A reservoir system for the big rain numbers would have to be in place throughout the show, unlike some previous productions that had moved in huge tanks at the key moments. It would also require a floor solid enough for tap dance numbers and non-slip enough for the rain downpours.

The solutions for making this work for a worldwide tour would rely on a combination of technology, timing and garden furniture.

TURNING IDEAS INTO REALITY

Another of Simon's concerns was creating a believable period setting. Of course, it would be essential for the production to have a spectacular arena for the lead character, Don Lockwood's, joyful rain dance, immortalised by Gene Kelly in the MGM movie. One problem was all of the changes of scene in the original movie. Simon decided to recreate the back lot of a 1920s Hollywood studio – a filming area for external scenes – which would be the setting for the entire performance, so that no extra scenery had to be brought in from the wings. For the famous dance, the character would be seen to switch on a giant rain-effect system within

The pool area is lined with a one-millimetre-thick PVC-coated fabric, lacquered with high mechanical strength. Then a three-millimetre-thick Correx floor protection is laid on top. This is fluted and helps drain the water as it is removed. Finally, a stainless steel frame that supports the decking is placed on top © Water Sculptures Ltd

the studio rather than perform out in a street.

Simon knew that he wanted deep puddles for the dance number. He wanted to recreate the playfulness of Gene Kelly's film performance when the star not only splashes but jumps into puddles of water. However, it would not be possible to project enough water down from rain bars in the short period of time needed to create these puddles for a five-minute dance sequence onstage; there simply would not be enough time. The whole stage area needed to flood, with a supplemental supply of water to create the illusion of puddling.

The 'eureka' creative moments for this project came in gardens. The first was in Simon's own garden: he was toying with a slatted garden table lying upside down on a waterlogged lawn and when he pushed it downwards, he noticed that the water came up over the slats. This gave him the idea of the water coming up from below rather than from above.

Then, at a friend's barbeque, he noticed some composite decking boards with narrow-spaced grooves. The hosts told him that these were made of recycled hardwood fibres with a recycled polythene bonding agent that had great anti-slip properties, especially when wet. The grey colour of the hard-pliant boards also fitted in with the black and white décor he had chosen for his silent movie film set. Now, all he needed to do was find someone who could turn his vision into reality. He turned to Morecambe-based Water Sculptures Ltd, which creates both indoor and outdoor spectacular water effects for events such as Olympic and Commonwealth Games displays, business inaugurations, and theatrical performances.

CHALLENGING WATER EFFECTS

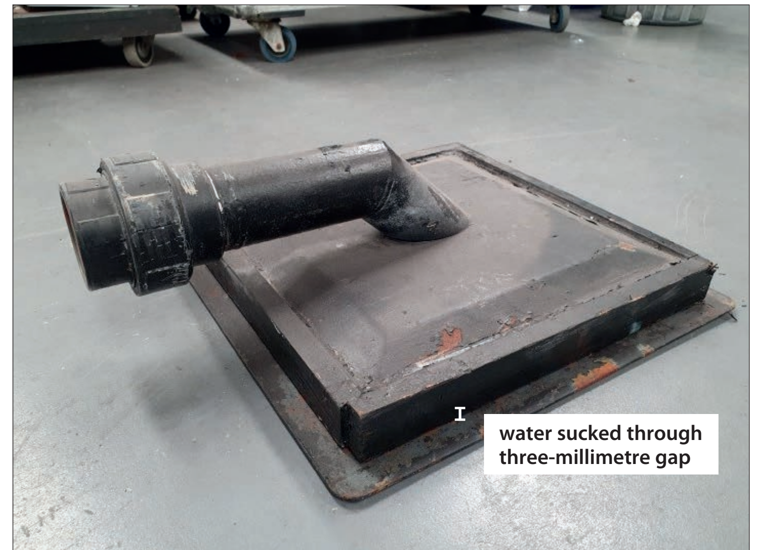
Simon had made things easier for Technical Director William Elliot by positioning the eponymous dance sequence just before the interval. This allows the technical team to deal with the excess water while the curtains are drawn. To get extra value out of the rain-making budget, the director and Simon had added a closing dance number whereby all the dancers dress as Lockwood and perform a final dance that also uses the rain effects.

William saw three main challenges. The first was that the touring element meant that the system needed to fit the stages and set up times of every venue on the world tour, so phone calls determined the space and expertise available at each theatre.

The second challenge was to solve the problem of how to get massive amounts of water onto and then off the stage area while creating a believable rainstorm.

The decking board area that has the pool reservoir underneath measures 7.9 metres across, 7.3 metres long and has a 15-centimetre aluminium wall rim all around to hold in the water. Of the 10,000 litres stored, the pool area needs the amount of water equivalent to roughly 13 bathtubs to overfill it and provide two centimetres of puddle depth above the decking. A further six bathtubs of water is required to supply the rain heads for each rain and dance sequence.

William thought that the flat stage would mean that gravity would neither deliver the water fast enough to fill the pool nor empty it in time. So, his team devised a flood-and-suction system with 1½ kilowatt pumps that delivers the water at a fast and controlled rate through a pair of five-centimetre delivery and suction hoses situated either side of the stage. From the show's beginning, there is a preset level of five centimetres of water sitting within the reservoir area below the decking, then a combination of pumps and rain from above floods the stage in one minute. While the engineering springs to life beneath his feet, the Lockwood character gently strolls the stage, setting the scene before launching into four minutes of a dancing and splashing tour de force.



The 'elephant's foot' has a greater surface area than that of the pipe connected to it. The shallow inlet allows the water to be sucked out to an extremely low level without the cavitation effect and without the intervention of a traditional submersible pump © Water Sculptures Ltd

Water Sculptures has produced rain for musicians Rihanna and Take That, actors James McAvoy and Sir Ian McKellen, and many others over the years

ELEPHANT'S FOOT

The major issue in William's second challenge was how to remove the water from the stage quickly and quietly before it overfilled. Because the pool area was shallow, cavitation would occur when drained with a pump and make loud gurgling noises – when cavitation takes place, air bubbles are created at low pressure and as a liquid passes from suction side to release side, the bubbles implode and create a shockwave.

The Water Sculptures team could see that this would be a problem: it would be both noisy and inefficient. The team came up with a low suction device, which then developed into a 45-centimetre-square plate with a five-centimetre outlet on it that sits at the bottom of the pool at the front of the stage. This was dubbed the 'elephant's foot': essentially a box with a shallow inlet.

The elephant's foot allows the water to be drained out of the pool to a very low level without losing the prime of the pump. The reservoir empties much more quickly and with less chance of it noisily cavitating. During the Lockwood dance it prevents the reservoir from overflowing; then when the rain stops and it is time for the interval, the water level is drained more slowly to the pre-fill level of five centimetres in preparation for the reprise at the end of the show.

Water Sculptures has fine-tuned this innovation and for performances of *Madam Butterfly* at the Royal Albert Hall, which required a shallow water system, the team drained 55,000 litres in just 12 minutes – a greater water volume than previously.

RAIN HEADS AND WATER SAFETY

Water Sculptures has produced rain for musicians Rihanna and Take That, actors James McAvoy and Sir Ian McKellen, and many others over the years. William's father and company founder, Byll Elliot, discovered that a nozzle tip used for washing the interiors of heavy-duty industrial process tanks, which came with a variety of apertures and pressures, could be adapted to make realistic rain in different theatrical and commercial settings – from a mist or light rain to a heavy downpour or even a deluge.

The company still uses the same techniques and employed heavy droplet nozzles for this production. These are hung from the theatre barrels, retain the pressure until the valves are open and, when released, produce the rain effect with

The character of Don Lockwood in the water that has been engineered to flood the stage © Jonathan Church Productions

each nozzle delivering about 33 litres per minute at 2.5 bar: a 120% increase in water volume on a standard domestic tap, at a similar water pressure. There are 24 nozzles on set that deliver at least 1,000 litres per minute during the rain sequences.

William's third challenge was how to safely store and heat the water used. Actor health is paramount, and warm, sitting water is a known hazard for bacterial growth, so four nine-kilowatt heaters warm the water to 28°C for performer comfort. The water is stored in two large tanks and a mini-filtration plant acts like a portable swimming pool plant. The water is treated with bromine tablets to kill any bacteria and a 110-watt ultraviolet steriliser has been installed. The whole system aims to maintain a pH level of 7.4, with the water changed every second week. All interior wet surfaces are cleaned with an antibacterial solution when drained.

ON THE ROAD

The Chichester Theatre's production of *Singin' in the Rain* turned out to be its most financially successful musical ever. The production transferred to the West End for two and a half years and then toured Russia, Australia, Japan, South Africa and Brazil. The rebooted version has been booked into Sadler's Wells Theatre for performances in 2021 and is due to tour Japan and Russia again in the future.

There will be differences between the production that has been touring the world and the one that will be at Sadler's Wells, as the team is still solving problems as they arise. Simon is aiming to reduce the current number of 15 lorries needed to transport the show for sustainability purposes. One possibility is to reduce the amount of water used by making the reservoir even shallower. Tests will be done to see if it can be reduced to around 10 centimetres, which could halve the amount of water needed.

Whatever tweaks are made, the essential *joie de vivre* that thrilled original audiences will surely remain. Indeed, although warned they could get wet, many theatregoers expressly ask for front row seats so that they can get soaked and feel part of the onstage action.

BIOGRAPHIES

Simon Higlett is a theatre designer. He has created the onstage designs for a number of stage shows and operas across the world. Simon has also received the Manchester Theatre Award for Best Design, two TMA Best Design Awards and the Helen Hayes Best Design Award.

William Elliot is Technical Director at Water Sculptures. He has worked at the company since 1984 and has travelled the world creating water spectacles for high-profile clients including the Royal Jordanian Family, 2012 London Olympics, Radio City New York, and Broadway West End Theatres.

Robotic systems are transforming how surgery is carried out in operating theatres across the world. This robot is controlled by another robot in a separate room but can stay in the treatment room during endovascular procedures to accurately advance guidewires and catheters, meaning that healthcare workers do not need to expose themselves to X-rays © Hamlyn Centre robot-assisted endovascular intervention technologies research group and Mr Jiwoo Choi

ROBOTIC ASSISTANCE

Robotic systems are increasingly in use in all aspects of our work and lives, and hospital settings are no different. Science writer Geoff Watts spoke to the engineers who are providing high-tech support to surgeons, which is making the surgical process simpler, quicker and more efficient.

Surgery is a three-dimensional craft skill, but one in which practitioners are sometimes hampered by an incomplete sense of what confronts them. Human tissue varies from translucent to opaque, so surgeons' only guide to what their scalpel tips are approaching as they cut into a tissue is their anatomical knowledge of what should lie below its surface and exactly where. The process would be easier if a tissue could be rendered partially transparent, allowing the surgeon to visualise particular vessels, bones, nerves, or whatever lying beneath the surface is being cut and helping to either find or avoid them.

Although such magic is not available, it can be simulated through augmented reality. This technology is one of many being explored in attempts to boost the effectiveness and safety of surgery, whether performed by surgeons using their own hands or working through the intermediary of a robot. Imperial College London is one of the leaders in work of this kind. Its Hamlyn Centre for Robotic Surgery was established to develop innovative technologies that can "reshape the future of healthcare"; it emphasises the importance of translating ideas into patient benefits.

Ferdinando Rodriguez y Baena is Professor of Medical Robotics at Imperial College London and co-director of the Hamlyn Centre. He points out that academic bodies such as his can think broadly about tackling society's health problems without having to focus too firmly on the financial consequences of failing to come up with something marketable. They can partially de-risk the early phase of innovation.

AUGMENTING REALITY

The exploitation of augmented reality by engineers at Imperial College London was originally carried out in partnership with one of its associated hospitals, St Mary's in Paddington. As a major trauma centre, St Mary's is accustomed to repairing limbs damaged in road traffic and other accidents. In addition to multiple fractures, these may involve soft tissue damage requiring surgical reconstruction using pieces of skin and underlying tissue, complete with their blood vessels, taken from adjacent regions of the body. For this transplanted tissue to survive and grow, its blood supply must be restored by connecting it to vessels in the region of its new home. Various methods can be used to locate these vessels, notably Doppler ultrasound machines that detect the presence of flowing blood.

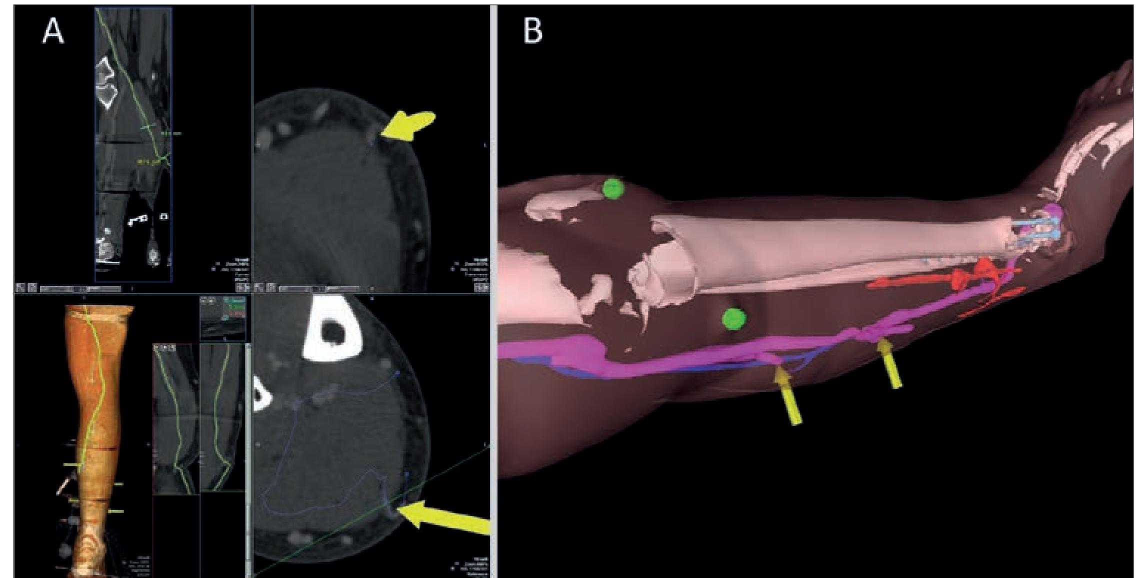
Dr Philip Pratt is a senior scientist at the Helix Centre, the university's Digital Health Innovation Lab, and formerly an associate of the Hamlyn Centre. He believes that augmented reality can make an effective contribution to some forms of complex surgical reconstruction. To test this, working with patients who had suffered severe leg injures, his medical colleagues carried out a computed tomography (CT) scan of the entire length of an injured patient's limb. The resulting data allowed radiologist Dr Dimitri Amiras to identify and map the various structures within it – bone, blood vessels and so on – and form a 3D image of the leg in which only structures of interest to the surgeon show up.

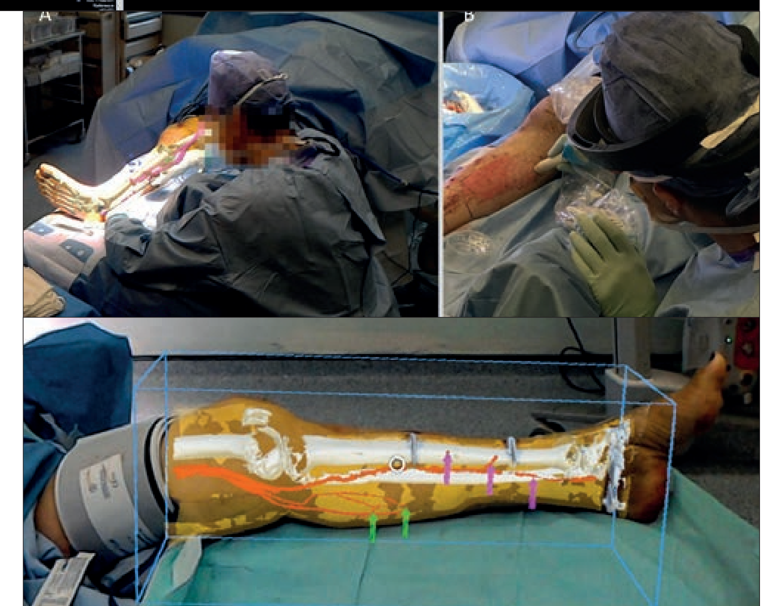
To exploit this image in the operating theatre, Dr Pratt devised software that would allow it to be fed into a Microsoft HoloLens headset. These headsets allow the user to see the real world, overlaid with computer-generated 3D imagery – in this case, models generated from the CT scan of the patient's leg. Once the surgeon has brought the two sets of images into alignment, they can visualise the limb as if the tissues surrounding and masking the main blood vessels have become transparent. The vessels can be more easily located.

Following a pilot study of five cases, the surgical team that had used the system described the new approach as more reliable and considerably quicker than using conventional Doppler ultrasound. However, Dr Pratt believes there is still room for improvement in the system. For example, alignment of the real-world and the computer-generated images of the limb has so far been done manually by the user. In principle it should be possible for the system itself to do this, allowing the surgeon to don the headset and begin operating immediately. In the study it took about hour from the time the patient was scanned to generate the enhanced image. Dr Pratt foresees this eventually being reduced to a couple of minutes.

Dr Pratt is now a co-founder of a startup company, Medical iSight, which was created to develop augmented reality for this and other surgical procedures. One such is mechanical thrombectomy, a technique in which a micro catheter bearing a small grab is guided through an artery in the groin and up into the brain to remove a blood clot in patients who have suffered some forms of stroke. Doctors already do this using real-time X-ray guidance provide by a pair of screens showing the position of the catheter tip in the body, but the task of navigation is still challenging. By presenting the operator with a 3D image of the grab on its intravascular journey, using a HoloLens headset would make it much easier.

Dr Pratt is certain that high-tech guided interventions will eventually become a routine feature in many kinds of existing and yet-to-be-invented medical and surgical procedures.

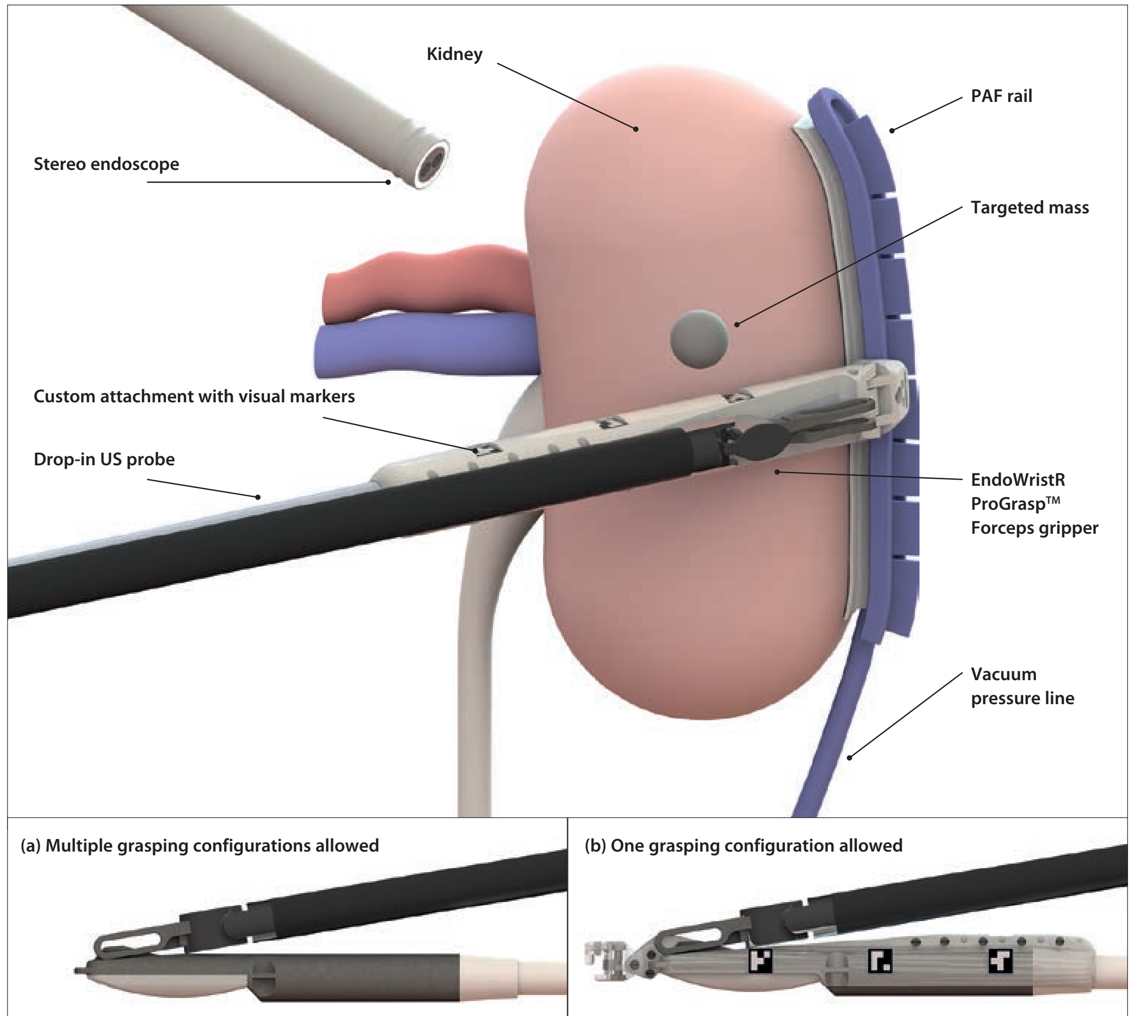




[Clockwise from top] Original imaging showing the location of injuries; example HoloLens rendering of patient's leg; augmented reality overlays being used in clinical practice © Images used under Creative Commons licence[1]

INSPIRED BY BIOLOGY

Another group of engineers, scientists and doctors with an interest in applying technology to medicine is based at the Wellcome/EPSRC Centre for Interventional and Surgical Sciences (WEISS) in University College London. The Surgical Robot Vision group, led by Professor Danail Stoyanov, is developing a device to be used in conjunction with existing surgical robots such as the da Vinci® machine (see 'Robots in theatre', *Ingenia* 58). The task they set themselves – to develop some means of holding an organ firmly and preventing it from moving while it undergoes an ultrasound scan during surgery – sounds simple, but it is not.



An overview of how the PAF rail system operates when used to guide a probe for robot-assisted partial nephrectomy procedures. The rail keeps the organ still allowing the probe to outline the tumour margin accurately

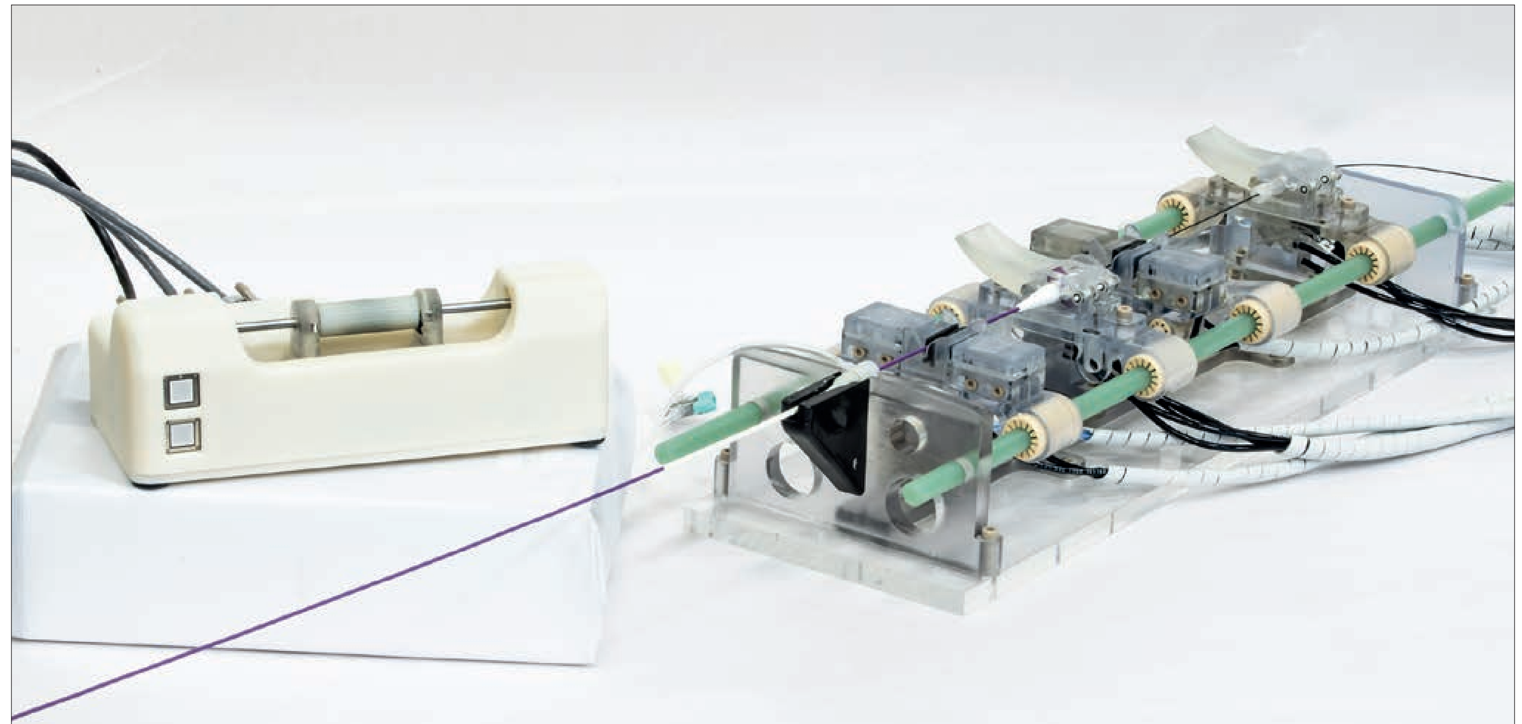
The group's interest was prompted by robot-assisted partial nephrectomy, a procedure intended typically to remove cancerous tissue from a diseased kidney. The extent of the cancerous tissue is identified using an ultrasound probe introduced into the patient's abdominal cavity via one of the trocars, through which the instruments the robot requires for the operation itself are also inserted. Inside the body, and in the grasp of robotic forceps, the probe is swiped across the surface of the kidney to generate the required ultrasound image. Although the forceps tool, which is a kind of miniature wrist with comparable range and freedom of movement, is effective at holding and manipulating the probe, the task is still challenging. In practice, probes often slip off the target and must be repositioned, which is distracting, time consuming, and one more cognitive task for the surgeon operating the robot.

The group's solution is inspired by biology and what they call a pneumatically attachable flexible (PAF) rail, which comprises a thin flexible tube attached to a vacuum source. The final ten or so centimetres of one side of the tube is fitted with a row of suckers that open out of it, while the other side carries a flat platform. Once the PAF rail has been introduced into the body cavity and manoeuvred into position on the surface of the kidney, it is held in place when suction is applied through the tube, and so to the suckers.

The device is a called a PAF *rail* because the perimeter of the platform is bounded by a T-shaped ridge. This acts as a rail on which the ultrasound probe can be located without slipping off, and along which its swiping movements can be directed. Moreover, the grip of the PAF rail to the kidney is sufficiently firm to use it for moving and repositioning the organ so that otherwise hidden parts of it can be brought to view.

The device is made of a rubber-like material, which has to be sufficiently flexible to bend to the curve of the kidney it is placed on, but also stiff enough so that the ultrasound probe can be coupled to the organ. To resolve this conflict, different components of the PAF rail are fabricated from variants of the material with appropriately differing degrees of hardness.

A patent has been applied for and the device has so far only been tested on animal organs. The length of the PAF rail can be chosen according to requirements, and project lead Dr Agostino Stilli can envisage it also being used for procedures carried out on other organs.



The control robot (left) and follow robot (right). The latter stays in the treatment room with the patient, while healthcare professionals use the first robot in the control room to guide its trajectory © 2019 IEEE. Reprinted, with permission, from *IEEE Proceedings*[2]

Intriguingly, the PAF rail's capacity to adhere temporarily but firmly to an organ while causing no apparent harm is of interest to surgeons operating non-robotically. Moving or repositioning an organ by, for example, grasping it with forceps is more likely to cause injury than using a suction device. This has prompted the research group to mount a further investigation of the PAF rails simply for this very basic purpose.

DISTANT GENTLE GUIDANCE

Another group based at the Hamlyn Centre[2] has been taking a critical look at robotic devices developed, or still in development, for endovascular interventions in heart disease. Using minimally invasive image-guided techniques such as coronary angiography, these interventions now play a key role in investigating and treating heart disease. The advent of robotics in this field is a more recent development.

To steer their guidewires and catheters from the point of insertion in the patient's arm or the groin, through the vascular system and into the heart, clinicians use fluoroscopic imaging, which uses X-rays to obtain real-time moving images. Staff are inevitably exposed to X-rays, despite shielding. The use of a system that has a control robot and a follower robot avoids this. Once the guidewire and catheter are inserted into the patient, staff can move to the control room where the first robot is located while the second stays in the treatment room.

When working without a robot, doctors move their guidewires using a combination of back and forth and rotational movements, monitoring the progress of the wire's tip by watching the image on a screen. In reviewing the various designs of existing control robots, the Hamlyn team noted that the human-machine interface most often adopted for steering the guidewire is a joystick: a method of control quite unlike that of long-established manual procedures. Surgeons trained to perform these surgical interventions would have to acquire a different skill to carry them out with a robot.

When the team set out to build a robot that avoided some of what they saw as the inadequacies of those already developed, this consideration played a key role in the design. The robot's control handle has a short round cylinder that can be slid back and forth on a horizontal rod. To instruct the pneumatically powered robot in the treatment room to move the guidewire and catheter, the handle on the control is moved forward; to rotate the wire the handle too is rotated. The finger and thumb grip, and the movements required to control the guidewire, are pretty much those used when performing the procedure non-robotically. Haptic feedback, which creates an experience of touch and is absent from most other systems that rely simply on what the operator can see on the screen, ensures that excessive and potentially damaging force to the walls of the blood vessel is never applied through the wires.

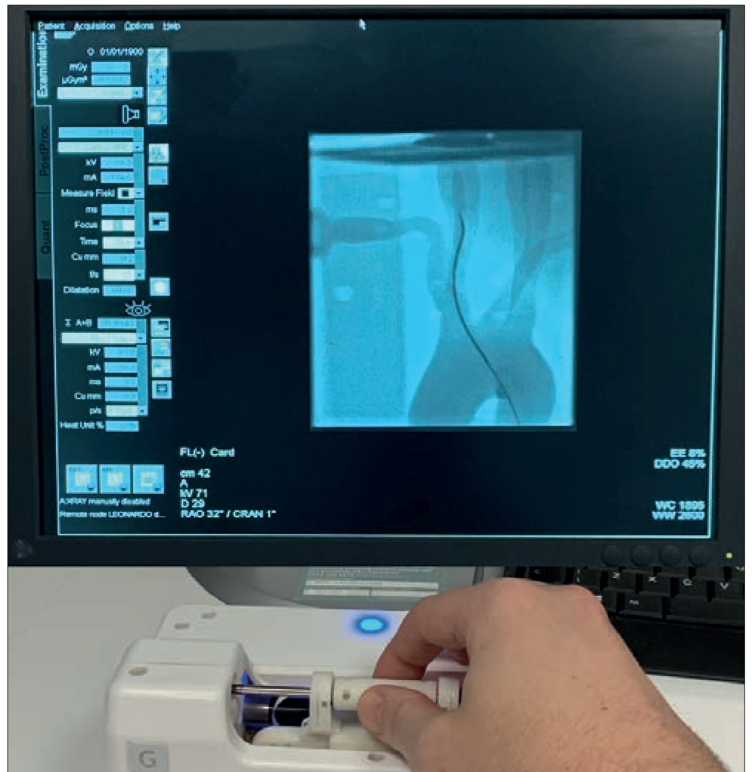
According to Professor Stoyanov, in the next 10 or 20 years, robots, robotic assistance and associated novel gadgetry along with new imaging technologies are going to become ubiquitous in operating theatres

Other features of the Hamlyn team's system include the treatment room robot's materials being compatible with magnetic resonance imaging; that the system can be used with any of the catheters and guidewires generally available; and that switching from robotic to manual control is quick and simple. The team reports good feedback from vascular surgeons who have tested the system using a full-scale model of heart blood vessels and in animal trials, but human trials are still some way off.

HIGHER TECH FUTURE

According to Professor Stoyanov, in the next 10 or 20 years, robots, robotic assistance and associated novel gadgetry along with new imaging technologies are going to become ubiquitous in operating theatres. Professor Rodriguez y Baena says that robotic surgery experienced a peak of development in the 2000s, which decreased towards the end of the decade.

Now, interest in novel devices that can improve the safety and efficacy of robotic operating systems, or make them more versatile, is once again on the increase. Although current practice in robotic surgery is still dominated by operations on the prostate gland and the kidney, surgeons are already exploring its benefits in procedures ranging from the treatment of rectal cancer to the repair of heart valves. The greater the need for precise cutting and sewing, and the more inaccessible the tissues requiring attention, the greater the benefits of a successful robotic intervention. With the ever-accelerating rate of technological advance in software, especially in machine learning, the progress of robotic and other high-tech surgical assistance may prove unstoppable.



The robot's control handle can be moved forwards and backwards and rotated to guide the treatment room robot's wires through blood vessels © Hamlyn Centre robot-assisted endovascular intervention technologies research group

BIOGRAPHIES

Dr Philip Pratt is a senior scientist at Imperial College London's Helix Centre and Co-Founder of Medical iSight. He is at the forefront of research into image-guided surgery, and has translated new technology into clinical practice.

Professor Ferdinando Rodriguez y Baena is Professor of Medical Robotics at Imperial College London and Co-Director of the Hamlyn Centre for Robotic Surgery.

Dr Agostino Stilli is an Assistant Professor in Medical and Soft Robotics at University College London, Co-Investigator in the Surgical Robot Vision group and a Rosetrees Enterprise Fellow.

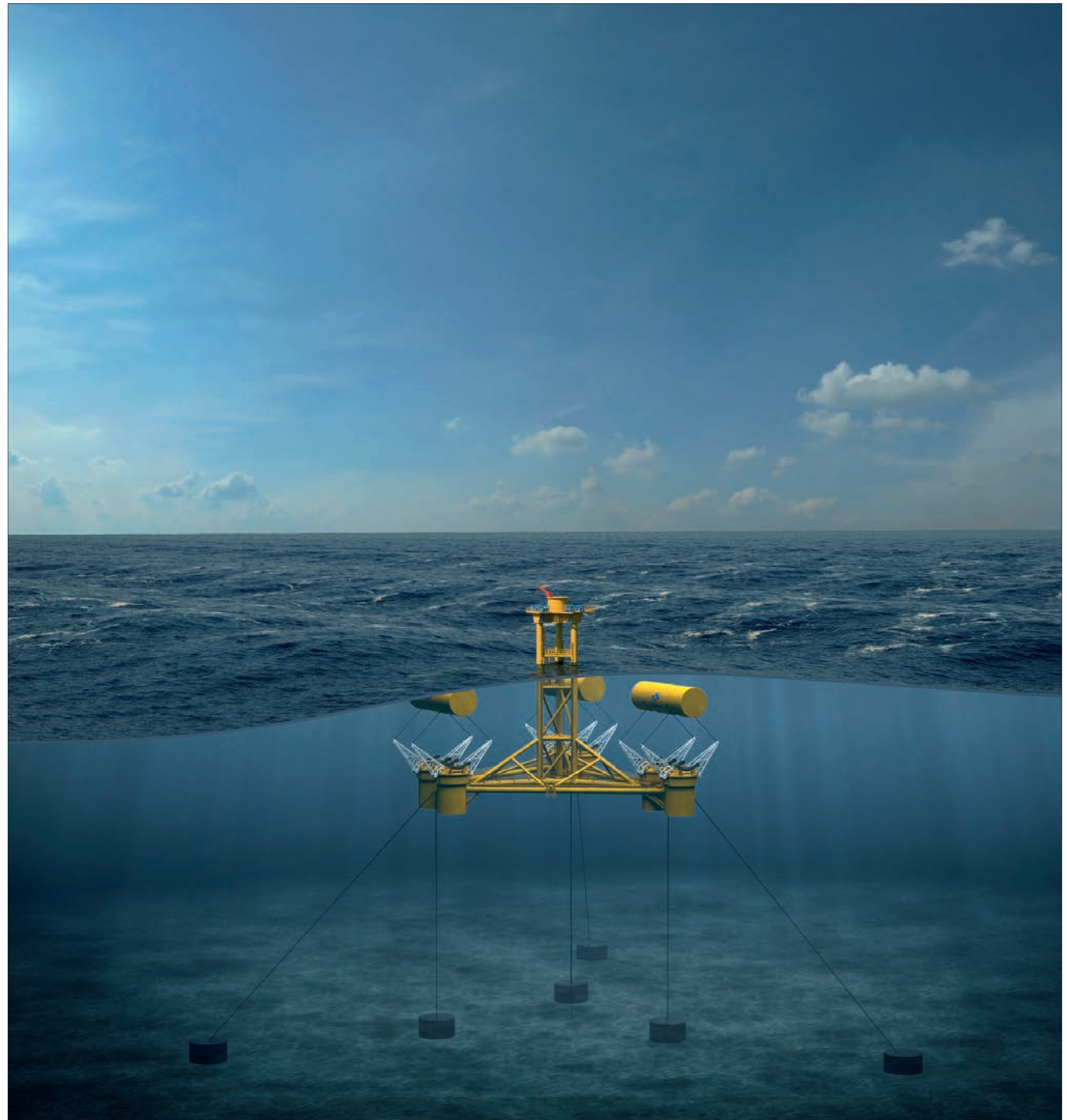
Professor Danail Stoyanov is a Professor in Computer Science at University College London specialising in robot vision for surgical applications, Director of the Wellcome/EPSRC Centre for Interventional and Surgical Sciences, and a Royal Academy of Engineering Chair in Emerging Technologies.

Dr Giulio Dagnino is a Research Associate at the Hamlyn Centre for Robotic Surgery, Imperial College London, working on robot-assisted endovascular intervention technologies. He has spent more than ten years working on image-guided robotic surgery.

[1] Pratt P, Ives M, Lawton G et al. (2018) Through the HoloLens™ looking glass: augmented reality for extremity reconstruction surgery using 3D vascular models with perforating vessels. *Eur Radiol Exp*: https://doi.org/10.1186/s41747-017-0033-2

[2] Abdelaziz M.E.M.K, Kundrat D, Pupillo M, Dagnino G, Kwok T.M.Y, Chi W, Groenhuis V, Riga C, Stramigioli S, Yang GZ (2019) 'Toward a versatile robotic platform for fluoroscopy and MRI-guided endovascular interventions: a pre-clinical study', *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Macau, China

TURNING THE TIDE



Marine test centres are helping engineers to test energy-generating devices in controlled settings © Marine Power Systems

Marine energy is the largest untapped source of renewable energy. However, generating energy from the oceans has challenged engineers for 50 years. Neil Cumins reports on two offshore renewable energy centres at opposite ends of the country, and the wave and tidal energy projects they have helped to refine.

As an island nation with an estimated 20,000 kilometres of coastline, the UK is well placed to harness energy from its oceans. Yet despite the first patent for wave power being filed in France back in 1799, it was the mid-1970s before the British government began seriously exploring the potential for coastal and offshore energy generation. By 1982, with North Sea oil abundant, the government abruptly terminated its wave energy programme, and it would be many years before this fledgling industry regained the momentum it had lost.

While wave and tidal energy is a potentially attractive approach, it has faced significant engineering and cost challenges when compared to offshore wind. Slow adoption of wave and tidal energy is partly caused by the challenging nature of the oceans. They are incredibly hostile environments for any human-made device to survive in, let alone operate efficiently. Wave and tidal energy hardware is subjected to abrasion, corrosion, bio-fouling, and electrolytic reactions, while being battered by hurricane-force winds and the sheer power of tonnes of moving sea water. There are also different challenges depending on whether wave or tidal energy is being harnessed. The former relies on wind blowing over water, and wave energy devices have to withstand sudden gusts of up to 100 kilometres an hour. Tidal power exploits changes in sea level and tidal currents, making it far more predictable, but the UK's attainable tidal resource of 20 to 30 terawatt-hours per year is only around half the level offered by wave energy.

COAST's ocean basin can generate waves and currents to enable testing of new energy technologies © COAST, University of Plymouth

Because of the extreme weather conditions found offshore, testing new hardware or energy production processes rarely takes place in the depths of the ocean. Instead, prototypes and scale models are tested in relatively controlled environments. These increasingly sophisticated facilities can replicate the environmental challenges of the open ocean, while measuring and recording activity using advanced (and often delicate) monitoring equipment.

Two separate testing centres at opposite ends of the country are enabling partner organisations to develop innovative and robust solutions to the many challenges of offshore energy generation. Their work demonstrates how ingenious engineering can be used to harness some of the planet's most untameable natural resources.

THE COAST IS CLEAR

At the University of Plymouth, the Coastal, Ocean and Sediment Transport laboratory has been performing hydrodynamics testing since 2012. Known by its acronym COAST, the testing facility has already been used in 60 commercial projects as an alternative to expensive and time-consuming sea trials. Its centrepiece is a huge ocean basin that measures 35 metres by 15.5 metres, with a moving floor supporting a water depth of up to three metres. Below the surface, 24 two-metre hinge depth paddles, powered by electric motors and supported by pressurised air cylinders, counterbalance the water pressure. Each paddle is regulated by software capable of replicating mathematical models of recorded sea activity, generating multidirectional waves over a metre in height in tandem with recirculating currents. A prototype wind system has also recently been installed, to further improve the basin's flexibility as a test bed by replicating storms and freak weather events.

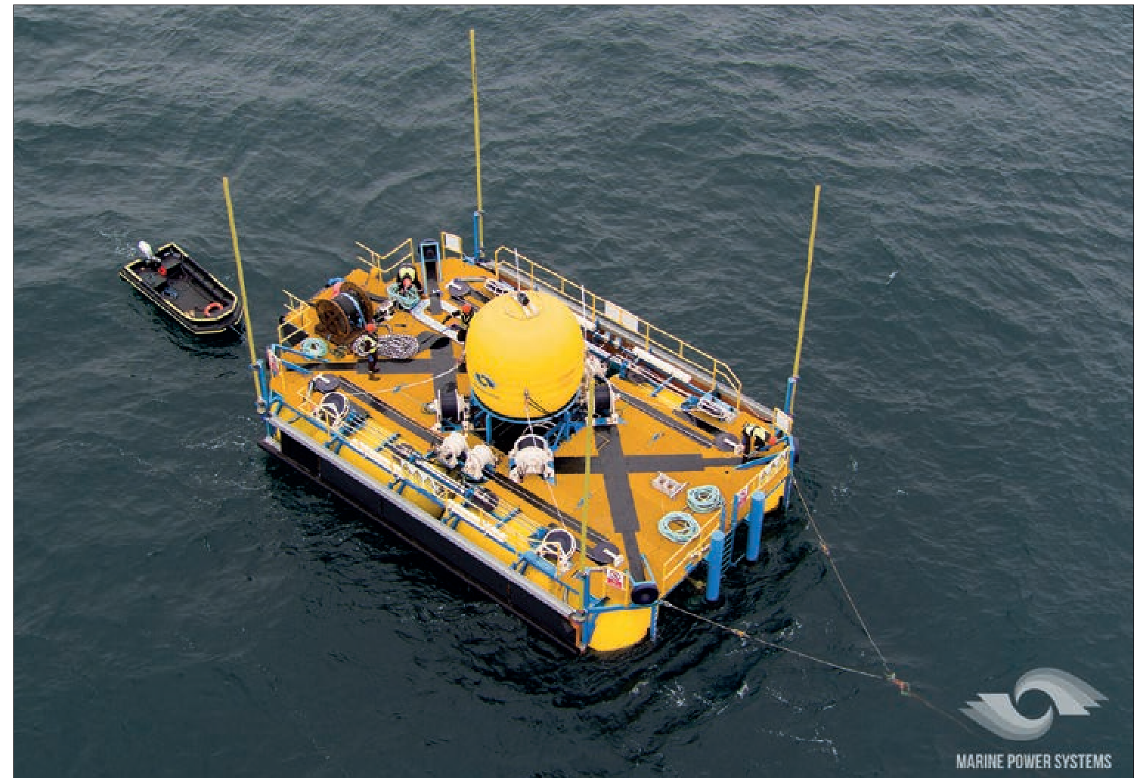
These realistic and repeatable sea states are ideal for manufacturers and energy providers to test and refine their hardware, as COAST's lead technician Alastair Reynolds explains: "Wave motion changes far more than other sources of renewable energy. Wind motion tends to be fairly consistent over a period of hours, whereas waves are constantly changing in their height, amplitude and power. A device capable of harnessing this energy must constantly adapt to changing conditions. Because of these issues, no design of wave energy converter has been accepted as the industry standard yet."

PREACHING TO THE CONVERTED

To date, three main types of wave energy converters have been developed:

- Oscillating water columns use trapped air pockets in a water column to drive turbines for electricity generation.
- Oscillating body converters convert wave motions into device oscillations to generate electricity.
- Overtopping converters deploy reservoirs to generate a head flow that subsequently drives turbines for electricity generation.

Each has different merits and optimal use scenarios – fixed oscillating water columns and overtopping devices work well along shorelines, whereas floating wave energy converters are generally required offshore. However, all three conversion methods face the same challenges, according to Professor Deborah Greaves OBE at COAST: "It is important for wave energy converters to survive extreme waves during hurricanes and storms. Most of the reliability and survivability studies undertaken to date have been based on computer modelling or laboratory scale tests, and long-term at-sea field experience is needed now to secure confidence in the sector. Excellent progress has been made in numerical modelling for wave energy convertor concepts and it is important to build on this to provide high precision analyses, especially under extreme wave conditions."



WaveSub harnesses the motion of sub-surface water particles © Marine Power Systems

MAKING WAVES

One example of a successful wave energy converter deployment involves WaveSub – one of a trio of devices manufactured by Swansea-based Marine Power Systems. This device is designed to produce utility-scale electricity generation from some of the most energetic wave climates on the planet. WaveSub comprises a tautly moored structure linked to three cylindrical wave energy absorbers, which captures and harnesses the motion of sub-surface water particles. Each WaveSub unit outputs a comparable level of power to a wind turbine and can be expanded into energy farms in much the same way. Captured energy is converted to grid-compliant electricity onboard the device, before being exported to the onshore electricity grid via subsea cables.

Since 2014, Marine Power Systems has regularly worked with COAST. Its research has included power capture investigations in directional seas, mooring layout trials, the development of multibody wave energy converters and the validation of numerical model simulations. Engineers can observe and validate complex problems, adjusting and refining their models within minutes. This has enabled them to increase the durability of motor waterproofing, while eliminating electrical interference and noise on signals – ensuring each WaveSub model is more robust and versatile than its predecessor.

COAST's controllable basin has been key to the development of WaveSub and other offshore renewable energy hardware, but precise measuring equipment also plays a crucial role in subsequent analysis. A set of nine Qualysis cameras can track six degrees of freedom motion to 1.5 millimetre accuracy, while high-speed cameras deliver slow-motion replays of split-second events such as wave impacts or prototype damage. An extensive array of strain gauges, pressure transducers and accelerometers also contribute to a data acquisition pool that is processed by custom-written LabView software. Similarly, the wave and current generation software was supplied by the same firm who designed and built the basins, to harness the full potential of those 24 individually controlled paddles.

TIME AND TIDE

While wave power is the most visible aspect of marine energy, tidal power offers an intriguing alternative – albeit with different challenges. Tidal streams are entirely predictable because the currents that cause them are formed in response to gravitational pull. For instance, the highest tidal ranges (rising and falling sea levels) are generated when the sun, moon and Earth are in line. This enables tidal power producers to calculate how much kinetic energy can be harnessed at any given point in time. Tides rise and fall twice a day, while many of the most powerful tidal streams occur where water is funnelled between islands, or between the coast and the seabed.

The Orkney Islands are ideally situated for harvesting tidal power, with tides flowing from the North Atlantic Ocean to the North Sea. As they pass through a narrow channel between the Westray and Stronsay Firths, marine currents reach speeds of almost eight knots (four metres per second). This is where Orkney-based European Marine Energy Centre (EMEC) established a grid-connected tidal test site, called the Fall of Warness. Seven cabled tidal test berths have been built across an area measuring around eight square kilometres, at depths ranging from 12 to 50 metres. Each cable feeds into a substation on the nearby island of Eday, with direct connections into the national grid and fibre-optic links to various switchgear and communications hardware.

The Fall of Warness is a tidal test site located in the Orkney Islands, where marine currents reach speeds of four metres a second © Orkney Sky Cam, courtesy of EMEC

The Fall of Warness has achieved several breakthroughs since it officially opened in 2007. The substation can redirect power produced by tidal testing devices to an electrolyser, making this the world's first tidal-generated hydrogen extraction facility. Technology such as droppable cameras and hydraulic cutters reduces the need for divers to enter the water, where they can operate for a maximum of 20 minutes per day – while tides have stopped during daylight hours. Meanwhile, a purpose-built onshore weather station feeds into a supervisory, control and data acquisition system. Supported by a historian database, the system sends device information, environmental parameters and electrical performance to a data centre. Clients can monitor their equipment in real time, controlling it remotely while conducting detailed analysis on performance and stresses.

TURBINE HAUL

This test-and-refine process was recently harnessed by Orkney-based Orbital Marine Power, which tested its SR2000 tidal machine at the Fall of Warness. During a week of continuous operation, it generated more than 116 megawatt hours – enough to supply nearly 7% of the entire Orkney Islands' electricity demand. The SR2000 was subsequently deployed in 2016 for a year of continuous operation, during which time its three gigawatt hours output exceeded the entire wave and tidal energy output in Scotland over the preceding 12 years.

The SR2000 has since been decommissioned in favour of a revised machine known as the Orbital O2, scheduled for completion at the end of 2020. Suitable for incorporation into large-scale arrays, each 73-metre floating superstructure has gullwing-style legs, which can be lifted above the water for maintenance or dropped below the surface for use. Each leg hosts a one megawatt steel turbine, whose 20-metre diameter creates the largest rotor area ever deployed on a single tidal generating platform. A 360-degree blade pitching control system allows these two counter-rotating turbines to capture power from both tidal directions without turning the machine to face the returning tide. The O2 can be reached by small boats at any tide, with most systems and components housed inside the floating superstructure to simplify access and inspection.

The SR2000 generated enough electricity to supply 7% of the Orkney Island's electricity demand during several weeks while on test © Colin Keldie, courtesy of EMEC

FUTURE PERFECT?

Neil Kermode has been the Managing Director of EMEC since 2005. He believes the marine renewable energy sector offers huge potential, despite being a relatively youthful industry: "Around the world, pretty much every turbine and wave machine deployed is experimental to some degree. However, the more often it is done, the less experimental they become and the more commercial the offering becomes." He argues that while practise makes perfect, it also makes things cheaper: "The more money that is invested in this technology, the more it can be demonstrated in real sea conditions, and the sooner it can be built out on a larger scale at competitive prices." The benefits are compelling: "We know we have the energy in the tides around our shores, and we now know we have the technology to harvest that energy. The UK has the skills to develop, install, maintain and remove the equipment, and we're going to need a lot more renewables to decarbonise our economy."

Global improvements in air quality recorded during the COVID-19 lockdown have thrown into sharp focus the need to reduce our reliance on fossil fuels for energy production, particularly if the UK is to meet greenhouse gas emissions targets by 2050. Despite the considerable challenges of harnessing wave and tidal energy, the abundant and renewable nature of wave and tidal energy offers many benefits. Tidal and wave energy devices are less visually intrusive than wind turbines or solar PV farms, raising fewer issues surrounding planning and potentially having less of an impact on wildlife. Underpinned by the world-leading research and development currently being conducted across the UK, wave and tidal energy are likely to supply an ever-increasing proportion of domestic power generation in the coming decades.

BLADE RUNNERS

The UK is the world leader in offshore wind power, which already generates 10% of the national electricity supply. Positioning turbines more than 40 kilometres offshore negates the aesthetic issues surrounding onshore wind farms, in turn permitting denser farms featuring blades measuring over 100 metres. These larger blades are less sensitive to wind speed variations than smaller onshore turbines, generating more predictable amounts of power. A single turbine can supply 12 megawatts of capacity, particularly since offshore wind speeds are usually much faster than over land. This is significant because power output increases as a cube of the prevailing wind speed: a turbine generates twice as much energy in a 25 kilometres an hour wind compared to 20 kilometres an hour.

Offshore wind energy poses significant challenges, some of which are shared with wave and tidal energy production. Extreme weather conditions can cause material damage, while it's hard to anchor turbines in water deeper than 60 metres. However, the latter problem has been resolved at the world's first floating wind turbine farm. Located 25 kilometres east of Peterhead, the appropriately named Hywind Scotland farm comprises five 254-metre turbines, anchored to the seabed by chains and thousands of tons of iron ore. These turbines collectively generate 30 megawatts of electricity, having achieved 65% of their maximum capacity during a hurricane while enduring eight-metre swells. That's an extremely high output ratio – 100% energy generation would require completely consistent wind at an optimal speed.

Hywind is one of 30 offshore wind farms within the UK's maritime waters. Installed capacity presently stands at over 8,000 megawatts, with 5,000 megawatts more under construction and a similar amount proposed for future developments. The offshore wind industry's ambition is to meet a third of the UK's electricity needs by 2030, producing 30 gigawatts of power, and it will rely heavily on British supply chains and expertise to achieve this target.

BIOGRAPHIES

Professor Deborah Greaves OBE is Head of School, Professor of Ocean Engineering and Director of the COAST (Coastal, Ocean and Sediment Transport) Laboratory at the University of Plymouth and is Director of the Supergen ORE Hub. In 2018, she was awarded an OBE for services to marine renewable energy, equalities and higher education.

Neil Kermode is Managing Director of EMEC, where he has overseen the deployment of more marine energy technologies in the seas around Orkney than have been deployed at any other site in the world. Neil is a chartered engineer, Fellow of the Institution of Civil Engineers and a Chartered Environmentalist.

In response to the COVID-19 crisis, engineering businesses have innovated and scaled up at speed, repurposing processes and production lines and accelerating design, certification and manufacture © Mike Fouque/Adobe Stock

RESPONDING TO A GLOBAL PANDEMIC

The COVID-19 pandemic has changed the world. As hospitals and healthcare workers across the UK have reacted and adapted to challenges posed, engineers and engineering businesses have stepped up to play their part, helping equip the NHS to address urgent needs. While there has been an enormous amount of disparate work done across the UK, **Rachel Jones** looks at a few examples around ventilators and PPE to highlight the different ways the engineering community has responded to the crisis.

An increase in the rate of COVID-19 infections led to the UK's engineering community gearing up to meet urgent social needs by innovating, repurposing and ramping up production. Since March, engineers in research and business have worked intensively to deliver solutions, often improvising at pace in close consultation with medical professionals.

At the outset of the pandemic, the NHS had just over 8,000 ventilators to save the lives of severely ill patients who developed breathing problems. An early projection suggested that more than 60,000 ventilators could be needed, and the UK's capacity for manufacturing ventilators was estimated at just 2,000 units per year. The government announced plans to source 30,000 new machines by increasing production of existing designs, importing thousands more, and commissioning fresh models. However, this projection was later revised to 18,000, meaning 10,000 more machines were needed.

As part of this, the government's Ventilator Challenge tasked businesses to make safe, easy-to-use ventilators, at scale, according to its specification for rapidly manufactured ventilator systems. Of 15 projects shortlisted by the government after about 5,000 initial offers, two of the most successful looked at how to reconfigure and accelerate production of existing models. Both came from the Ventilator Challenge UK (VCUK) consortium of industrial, technology and engineering firms, including Formula 1 teams, Airbus, Siemens, and Rolls-Royce. This lent manufacturing muscle to scale up production of a reconfiguration of Penlon's Prima – used in operating theatres – and Smiths Medical's ParaPAC, a mechanical system.

VCUK approached anaesthesia equipment manufacturer Penlon, which believed it could meet the specification by reconfiguring sub-modules into a more compact and affordable solution that was easier to manufacture. The existing production rate was between six and ten units a week, but the consortium needed to get closer to 3,000 a week. Production lines completing 250 different activities spanned from North Wales to Dagenham, Hampshire and Oxfordshire, involving 2,200 people.

One engineering challenge was to secure the supply of strategic components. Each of Penlon's reconfigured machines has about 700 parts, many obtained from other countries and some made using now-obsolete processes. "We had to reinstate production lines in Israel in order to produce printed circuit boards," said Dr Graham Hoare OBE FREng, Executive Director and Chair of Ford of Britain, who led this project on behalf of VCUK, at an online Q&A event organised by the Royal Academy of Engineering*. Another challenge was to train thousands of new workers. "We had to develop an entire remote training strategy," said Dick Elsy CBE, Chief Executive of the High Value Manufacturing Catapult and VCUK's Chair. "We used Microsoft HoloLens to train people in the production facility [from other locations] … and had well over 100 HoloLenses in use. It was remarkable how people responded and made the tools work."

Dr Hoare described how pressures that necessitated speedy execution helped to engender rapid new learning and collaboration. One example came from Siemens, which involved its apprentices to address a complex needle adjustment. This team created a digital twin of the manufacturing facility and the parts, solved the problem in the digital world, 3D printed the solution, tested it in production, and found a way of automating it in four days. Dr Hoare reflected: "That speed of execution is something we will take forward. We've learned that if you move very fast and fail very quickly, you don't actually set yourselves back. If we harness that, we will make much greater progress going forward."

In mid-April, the consortium's Penlon Prima ES02 gained approval from the Medicines and Healthcare products Regulatory Agency (MHRA) and the government ordered thousands of units. "We were very focused on getting everything ready," said Elsy. "It helped that Penlon is used to dealing with the regulator, but we achieved regulatory approval in 21 days – it normally takes six to eight months."

INNOVATIVE DESIGNS

Many of the engineers who joined the race to produce mechanical ventilators started from scratch. OxVent is a simple and scalable design put together in less than a fortnight, and conceived as an open-source, not-for profit project. A team of University of Oxford academics created a working prototype in four days, with help from technicians at the Institute of Biomedical Engineering. They worked to identify a mechanism requiring minimal moving parts, aiming

HOW MECHANICAL VENTILATION WORKS

The ordinary function of breathing involves an intricate and complex process. In normal breathing, when the diaphragm muscles tighten it expands the lungs, reducing the pressure in them and drawing air in. On relaxation, pressure in the lungs rises again forcing air out.

COVID-19 infections can make normal breathing very difficult. Inflammation can irritate the airway lining and alveoli: these tiny air sacs become clogged, pouring fluid and inflammatory cells into the lungs, and losing the ability to transfer oxygen to the capillaries, or dispel carbon dioxide. When a patient develops acute respiratory distress syndrome (ARDS), fluid builds up in the sacs and oxygen levels plummet.

As an illness unfolds, a patient may require mechanical ventilation, either non-invasive, invasive or both. This involves pushing oxygen-rich airflow into the lungs to help the patient breathe, which also frees up energy for the body to focus on fighting infection.

The first ventilators, such as the 'iron lung', came into use nearly a century ago and typically used negative pressure: making the chest expand and contract to suck air into the lungs. These fit over the chest and pull air in. These days, positive-pressure ventilators fit over the face and help patients breathe by pushing air into the lungs: blowing and stopping in cycles, ventilators enable patients to take in oxygen and dispel carbon dioxide.

There are three forms of non-invasive ventilation using positive airway pressure: autotitrating (APAP), bilevel (BiPAP), and continuous (CPAP), the latter of which has been used successfully with many COVID-19 patients. CPAP helps patients who can breathe by themselves, and involves channelling oxygen through a facemask to keep airways unobstructed. It works by applying mild pressure continuously throughout the breathing cycle.

A CPAP machine delivers a constant flow of pressurised oxygen-rich air to create a cushion along the upper airway: this helps to hold open the alveoli, but it does so continuously rather than only at the end of the exhalation. Patients remain conscious and may be on CPAP for up to four days.

Invasive ventilation, sometimes used for several weeks when someone is very sick, involves inserting a tube into the airway. The ventilation unit also has a humidifier to match air to body temperature and add moisture and can hold a constant amount of low pressure to keep air sacs in the lungs from collapsing. The tube allows mucous to be sucked away from the windpipe.

Today's ventilators are highly sophisticated, giving healthcare professionals more ability to monitor and tailor treatment to individuals.

to overlap as little as possible with the conventional ventilator supply chain. The simple design has a feedback loop to control flow delivered to the patient, but does not monitor the patient's physiological signals.

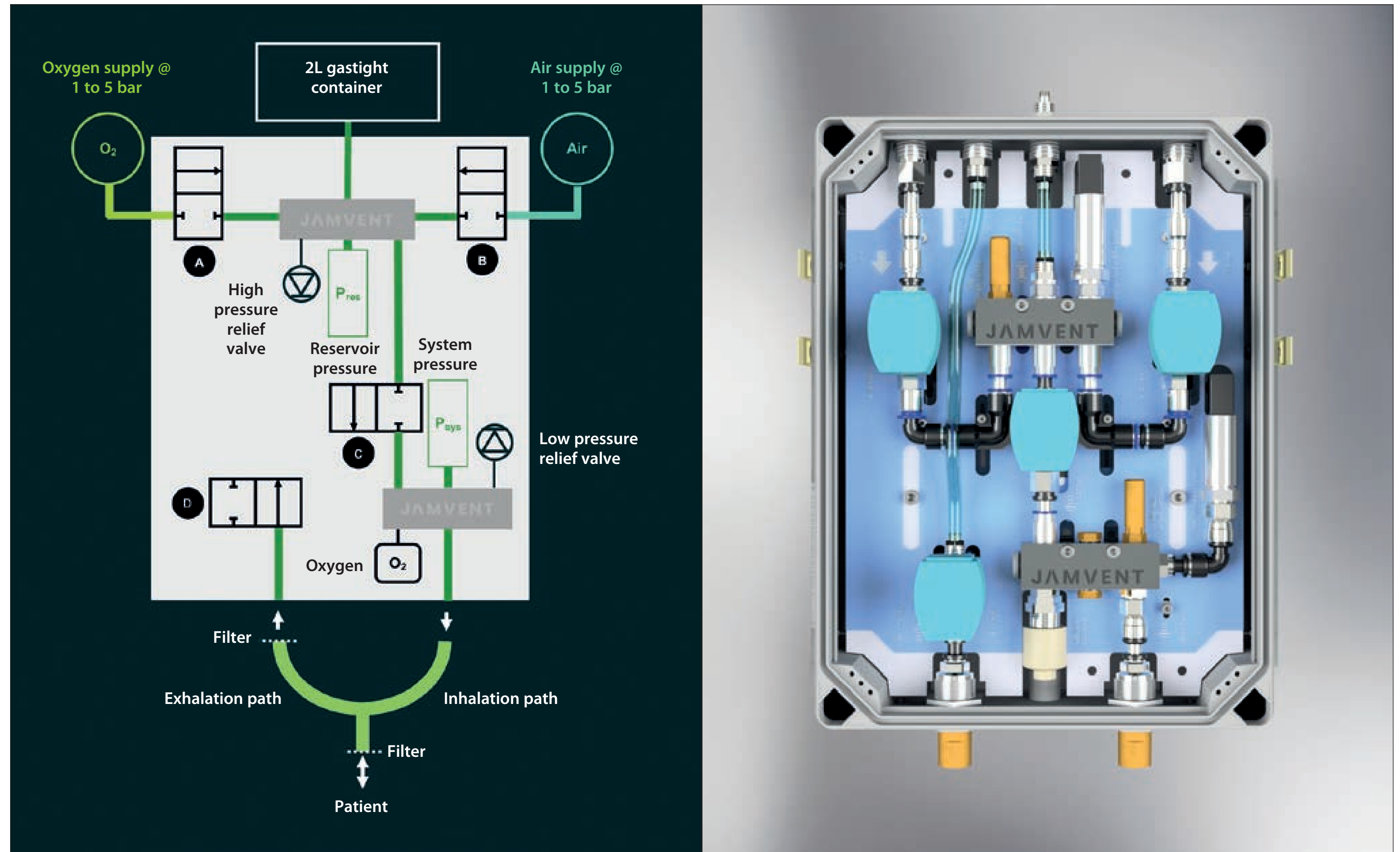
Testing and validation were a critical part of the rapid innovation process. Ventilators have a straightforward core function (see 'How mechanical ventilation works') but to sustain life reliably, a design must undergo rigorous and lengthy testing. Like the design, testing had to be developed from scratch, but the team found there was a run on testing equipment. "We had a lucky break: a colleague got us a measurement system to look at the characteristics of flow and volumes delivered in lung models, and that ended up being critical for our test methodologies," says Professor Tim Denison, Royal Academy of Engineering (RAEng) Chair in Emerging Technologies.

With the UK's need for ventilators no longer as critical, the government has not taken OxVent forward, but its team is now adapting the work to evolving global needs and aims to gain FDA Emergency Use Authorisation. It is also pursuing regulatory approval in countries where COVID-19 cases are increasing, and envisages OxVent's rapid manufacturability will see it come into its own.

Other projects aiming to help underserved health systems have been developed independently. Dr Jakob Mathiszig-Lee, an Imperial College London honorary clinical research fellow and senior anaesthetic registrar at the Royal Brompton Hospital, recognised that basic functionality would not be sufficient for COVID-19 patients. He took his ideas to RAEng Research Fellow Dr Joseph Sherwood, former RAEng Research Chair in Medical Device Design Professor James Moore Jr, and Dr Michael Madekurozwa at Imperial College London's bioengineering department. Together, they outlined clinical need and engineering requirements for a design, aiming to create a low-cost emergency ventilator model – JAMVENT – that could be assembled quickly and easily using simple components outside of the existing ventilator supply chain.

Importantly, engineers gave JAMVENT three modes: the clinically preferred pressure-regulated volume-controlled mode to deliver a desired tidal volume to the patient while controlling pressure; a mode to combine the application of suction with maintenance of pressure to keep the lungs open; and a crucial breath-sensing mode to assist patients ventilated for long periods redevelop their ability to breathe.

Compatible with hospital gas supplies and lower pressures provided by oxygen concentrators, JAMVENT delivers 100% of incoming gas to the patient and allows control of oxygen content. A key design feature of JAMVENT is that it doesn't use proportional



JAMVENT employs principles of fluid mechanics and uses two pressure transducers, an airtight container and a series of on–off solenoid valves to control the pressure of the air entering the patient's lungs, avoiding the need for a balloon to pump oxygen

solenoid valves, but instead uses simple on–off solenoid valves. These are cheaper, can be provided by numerous manufacturers worldwide, and are easier to maintain. Two on–off solenoid valves control oxygen and air inlets, allowing pressurised lines to charge up the gas reservoir with a single breath of oxygen/air mixture. Reservoir charging is regulated via pressure and tidal volume requirements set by the clinician. A third valve controls when the pressurised gas mix is delivered to the patient; it also enables measurement of flow rate based on pressure drop across the valve. A final solenoid valve sits in the exhalation pathway, closing when the lung reaches a desired pressure and allowing calculation of exhaled volume.

The research team developed computational models and artificial lung models to test performance, while Dr Mathiszig-Lee gave overall direction and provided answers to questions about technical requirements. The team upgraded the design to make it more modular, separating electronics and pneumatics for ease of maintenance. An important element of the work was to make the design available openly. Simple to assemble and operate, JAMVENT can be made from parts costing around £1,500 and can run from a standard PC (as well as from a medically approved touchscreen device). Parts can be sourced from various manufacturers at lower cost than proprietary components. "Each valve performs multiple functions, reducing the number of system components, improving ease of manufacture, reducing cost and enhancing supply chain flexibility," adds Dr Sherwood.

While this design was also not taken forward by the UK government, the team is now pursuing emergency regulatory approval from the FDA, with Forbes reporting its "potential to disrupt the emerging $5 billion ventilator market".

ALTERNATIVE VENTILATION

As the crisis unfolded and clinicians learned more about COVID-19, evidence grew that non-invasive methods of ventilation could offer an alternative way to alleviate illness, even in those with severe infections. Among those to innovate in this area were a team from UCL that worked with clinicians and Mercedes AMG High Performance Powertrains to reverse-engineer a CPAP device, now in development as UCL-Ventura. To save time, the UCL team decided to reverse-engineer the Philips Respironics WhisperFlow CPAP device, once used widely in the NHS but now off patent. This simple mechanical device allowed rapid prototyping and mass manufacture; and using it to demonstrate like-for-like to the MHRA in terms of performance and function would help the team gain regulatory approval more quickly. It looked for a manufacturing partner and turned to the Formula 1 (F1) community, which had set up Project Pitlane to support ventilator projects. With the Australian Grand Prix cancelled and F1 in shutdown, Mercedes AMG High Performance Powertrains Managing Director Andy Cowell FREng was keen to help.

Four Mercedes engineers arrived at UCL the next day, and Mercedes ordered its own WhisperFlow from Ebay. "By 10am the next morning, this device was in our CT scanner, then we set up a test rig, and were disassembling it and looked at the tooling required," Cowell told an online Q&A event**. To save time, one development engineer took the initiative to make adapters on his own rapid prototype machine that evening rather than wait for a new order. As well as a flow-generating device to plug into the hospital oxygen supply, other components were needed, including an oxygen analyser and breathing circuit.

With oxygen a limited commodity in hospitals, and the WhisperFlow relatively oxygen hungry, it was vital for the UCL-Ventura to improve oxygen utilisation. UCL's mechanical engineers worked closely with Mercedes to redesign the entrainment port and improve flow and pressure characteristics. Mercedes set up a rig to do flow tests on filters on the PEEP valves (a spring-loaded valve that the patient exhales against), making sure the total flow was manageable with reasonable pressure drops, while its simulation team – normally busy designing inlet ports and plenums and compressors for F1 engines – worked to improve fluid flow through the jet pump part of the flow device.

Going from initial idea to prototype testing in a hospital setting took 100 hours, and approval from the MHRA took another 10 days. This came at the end of March and coincided with NHS updating its care pathway to give CPAP prominence. In one evening, an initial order of 100 devices from the Department of Health and Social Care turned into an order for 10,000. "That evening was the culmination of all of the work we'd done up to that point, an incredibly intense two weeks," said Rebecca Shipley, Professor of Healthcare Engineering at UCL. "We shifted from development to being entirely focused on getting [the devices] out."

Mercedes repurposed five machining centres at its Northamptonshire facility. Putting pistons and turbocharger parts to one side, manufacturing engineers reprogrammed and retooled machines with a precisely defined cycle time to meet the 1,000 a day goal. Outside suppliers manufactured the device's three finely turned stainless steel needle valves: an on/off valve, a flow valve and an oxygen valve. This involved the challenge of ensuring drawing tolerances were robust enough for parts to go together. By 15 April, Mercedes had made 10,000 devices to meet the order. These were sent to around 60 NHS hospitals, and the UCL team has since released their designs through a controlled licence process.

One of the UCL team's key motivations was to contribute to the international response to COVID-19. It created a compare-and-contrast between the original WhisperFlow and the UCL-Ventura device, making available drawings, CAD models, assembly and test instructions, a generic schematic for the patient circuit, and pressure versus flow rates. The blueprint has already been downloaded more than 1,800 times across 105 countries including South Africa, Bulgaria, Peru, Mexico, and Russia. There is now an ongoing effort to gather and analyse patient data.

The project also yielded benefits for Mercedes, added Cowell. "We've learned there are a huge number of crossovers with the medical world: engineering is everywhere and this project shows our skillsets can be applied to this world in a useful way."

ENGINEERED PROTECTION

While some teams raced against the clock to help patients, others focused on protecting health workers by providing personal protective equipment (PPE). Vitally needed by not only frontline healthcare professionals but also sectors including food production, retail and construction, the government took steps in March to relax regulatory requirements for a limited time to speed up the supply of essential COVID-19 related PPE on to the UK market, in line with a European Recommendation. In the case of PPE, the easement reduced the number of tests that manufacturers need to carry out on PPE products to the minimum testing considered vital for PPE being used in a COVID-19 context and a healthcare environment. The approval procedures needed for products subject to regulation, known as conformity assessment (CA), are the procedures that manufacturers follow, working with a Notified Body for the relevant regulations, in this case PPE or medical devices (or both), to show they have used appropriate standards for their products, services or systems. The evidence base the manufacturer collects enables them to claim compliance with the essential health and safety regulatory requirements, which is shown by the CE mark. In a further move to accelerate the availability of PPE, the easement allowed manufacturers that had engaged with a Notified Body to make PPE goods available for use before completing the full CA process.

Aseptium and 4c Engineering, two companies located on the same Highland enterprise campus in Inverness, shared experience in technology development and access to a suite of rapid prototyping tools. In March, they approached their local hospital to see if they could assist with PPE for healthcare workers. "The clinical lead for intensive care said that they were short of face shields, and asked if we could look at that," says 4c's project manager Peter MacDonald. The companies launched Project Corran, with the team considering factors including protection level, comfort, size and shape, usage frequency, and design pointers from other models, as well as regulation, sourcing non-hazardous materials, and time- and cost-effectiveness.

With an initial request to make 400 Corran I face shields, the team soon realised that – even with four 3D printers at its disposal – production wouldn't be efficient. Instead, it opted to use components that could be sourced on the high street: clear PVC sheets, double-sided tape, foam and elastic. The aim was to make the design as easy as possible to assemble so others could replicate it elsewhere, and to use whatever resources were readily available to speed up the process. A prototype was ready within a week, which the hospital's infection control staff approved on a Friday afternoon, and volunteers from local companies joined the production line for the weekend. By Monday, 200 shields were ready to deliver.

CE marking of the Corran II involved making 45 prototypes, with the team using a laser cutter to form components into a complex shape and give a professional finish, with components nested on sheets to avoid wastage

Importantly, the face shield was conceived and made available as an open-source design. One group in Argyll used the design to make 5,000 units, while a school-based group in Skye made 2,000 more. "It can be made with a pair of scissors but people can also automate elements of manufacture," MacDonald explains. The Scottish consortium had itself produced 7,800 shields by the end of April.

Ongoing and urgent need for PPE meant the project soon entered a new phase. Prototypes were engineered not just to meet regulatory requirements but also to improve wearer comfort. Little changes had a big impact: Corran mark II incorporates tabs to hook up a mask to reduce pressure on the wearer's ears. The bend of the visor holder was also engineered to provide maximum comfort and ease of manufacturing, and modifications allowed components to be cleaned and reused. After testing by Notified Body SATRA Technology, Corran mark II is now a CE marked piece of PPE.

Another example of rapid innovation comes from a team that created a new form of powered air-purifying respirator (PAPR). A PAPR offers better protection than a respirator by using a fan to draw in air through a filter and channel it via an enclosed hood or mask. However, expense, noise, heaviness, and discomfort makes some models impractical for lengthy wear. The concept for

MEETING DEMAND

Many engineering businesses have repurposed equipment or pivoted production to respond to urgent needs such as Ricardo, which makes a range of complex products including engines and precision parts. At the pandemic's outset, it settled on helping produce PPE, supporting crowd-based 3D printing consortia using rapid prototyping tools.

It then sought to scale up production, collaborating with an injection moulding partner to create a tool capable of high-volume manufacture of face shields. Applying engineering design expertise to refine the original rapid prototype design, Ricardo's team invited local NHS doctors to give feedback. The next step was to turn two of its technical centres into temporary production lines.

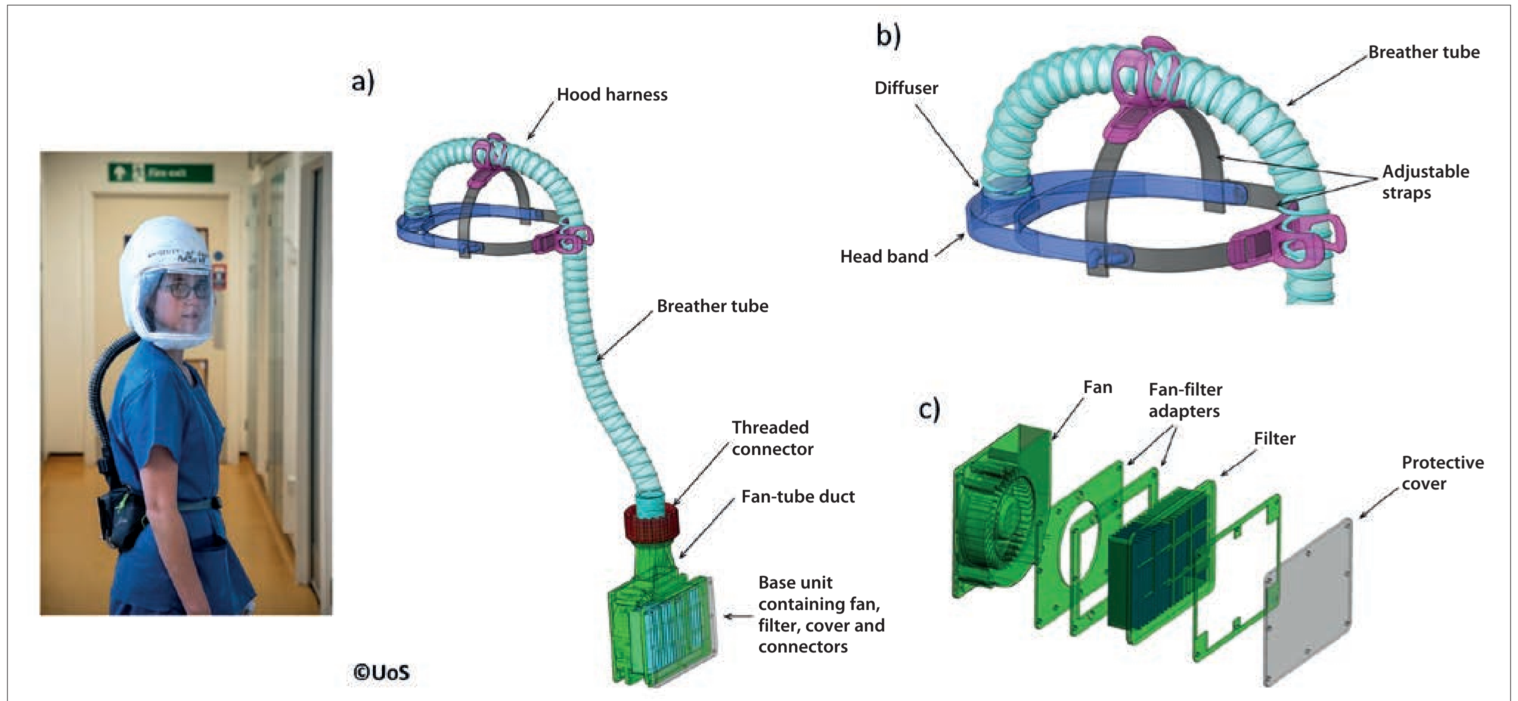
Remote working (because of the need for social distancing) was one of the challenges, according to Phil Mortimer, Technical Business Manager at Ricardo Automotive and Industrial. "We completed design reviews, held supplier discussions, set up a new manufacturing line and conducted testing with a team of people working remotely." Going from design concept to deliveries of PPE took just three weeks and the company worked with Notified Body SATRA Technology to secure fast-tracked testing of the product to the EN 166 Personal Eye Protection European Standard. Overall, Ricardo produced 10,000 protective face shields distributed to NHS hospitals, GP surgeries, care homes, and other services across the south of England and the Midlands.

As well as the unprecedented need for PPE, the crisis has generated enormous demand for another protective measure: hand sanitiser, which can help stop the virus's spread. Hexigone Inhibitors, a member of the Royal Academy of Engineering's Enterprise Hub, produced hospital-grade sanitiser.

Closure of construction sites meant that the firm – a chemical manufacturer that makes chromate-free corrosion inhibitors for coatings for buildings – had spare capacity in its large mixing vessels, normally used to make corrosion inhibitor. Adapting skills and resources to produce hand sanitiser was an obvious fit.

The firm set up its sanitiser manufacturing process with a team from Swansea University; the two then decided to increase output by operating independently. Via Innovate UK, Hexigone Inhibitors obtained a donation of 8,000 litres of isopropanol (the much sought-after main ingredient of hand sanitiser) from GlaxoSmithKline.

Sanitisers need to comprise 60% alcohol to be effective but Hexigone Inhibitors has made its batches to the WHO recommended formulation (75% alcohol) to ensure these eradicate coronavirus in healthcare settings. The recipe includes water (to dilute), glycerol (to moisturise), hydrogen peroxide (to kill spores) and lemongrass essential oil (as scent). The firm has now made 6,000 litres of sanitiser and is donating profits to Mental Health UK and local food banks.



The second prototype for the PeRSo was presented to University Hospital Southampton in late March and pilot testing led to further modifications
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a new version – now being manufactured as PeRSo – came from Professor Paul Elkington, Professor of Respiratory Medicine at the University of Southampton. Seeing the pandemic unfold, he realised clinicians involved in high-risk aerosol-generating procedures such as intubation would need a more comfortable respirator.

He took his ideas to colleagues including Professor Hywel Morgan, who led formation of an engineering team that included Dr Alex Dickinson, a RAEng Research Fellow and Associate Professor in the mechanical engineering department. "Within the week, we had a working prototype we took to University Hospital Southampton," says Dr Dickinson. "They gave us helpful feedback on our first prototype, and by the following Thursday we returned to them with a mark II."

Prototyping involved verifying the basic function in terms of filter efficiency by assessing bacterial growth on an agar plate inside the respirator, and looking at its ability to filter out droplets of a bitter-tasting chemical commonly used in fit-testing mask respirators. The team did extensive pilot user testing. The result is the lightweight PeRSo, consisting of a fabric hood, plastic visor, small portable unit delivering clean air through a high efficiency particulate air (HEPA) filter, and battery-powered fan mounted on a belt pack. PeRSo also shows the wearer's face, increasing comfort for both wearer and patient.

Dr Dickinson highlights decisions made in relation to projected use of PeRSo, considering materials, distribution of weight to prevent neck muscle fatigue, restriction in movement, and ease of cleaning and decontamination. Local firm INDO Lighting took PeRSo into further development, testing and manufacture, and the first 4,000 have been deployed at University Hospital Southampton with 6,000 more ordered for use across Hampshire. There is an active application in place for regulatory approval and the PeRSo is currently undergoing testing at BSI.

As with Project Corran, this project's key elements included the use of commonly available materials and making the design available to others. "We published an Open Specification as early as we could, and followed with full open-source design files once the prototype was more refined," reflects Dr Dickinson, who is now part of a team developing PeRSo for lower- and middle-income countries. "It was also important to collaborate, bringing in support at the right stage, such as partners for testing and large-scale manufacturing."

In extraordinary times, the engineering profession has contributed to the COVID-19 response through many more innovative projects and multidisciplinary efforts. The efforts of these engineers and organisations are just a fraction of the ways in which the community has mobilised to rapidly add expertise to the ongoing battle against the virus, as well as learning lessons from innovating and scaling at pace.

*Information and quotes about the Ventilator Challenge UK consortium were taken from an online Q&A event, organised by the Royal Academy of Engineering, with Dick Elsy CBE, Chief Executive of the High Value Manufacturing Catapult, and Dr Graham Hoare OBE FREng, Executive Director (Business Transformation) & Chairman, Ford of Britain, on 29 May 2020.

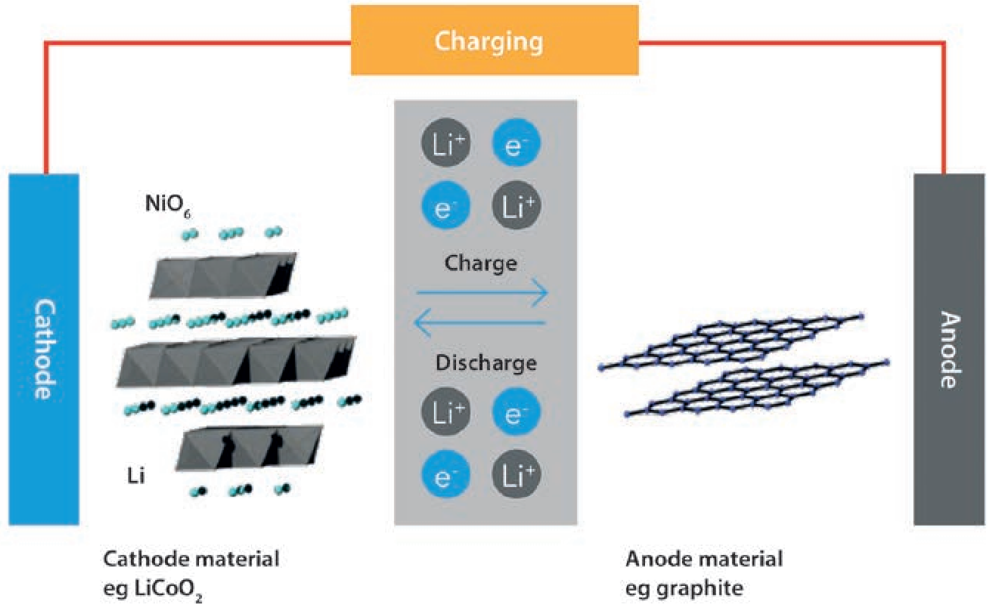
**Information and quotes about the UCL-Mercedes Ventura device were taken from an online Q&A event, organised by the Royal Academy of Engineering, with Professor Rebecca Shipley, Professor of Healthcare Engineering, Director of the Institute of Healthcare Engineering and Vice Dean (Healthcare), University College London and Andy Cowell FREng, Managing Director, Mercedes AMG High Performance Powertrains, on 19 May 2020.

To watch both of these webinars, as well as other in the series, please visit **www.raeng.org.uk/events/event-series/innovation-in-a-crisis-online-events**

Mass adoption of electric vehicles is key to reaching the UK government's goal of net zero greenhouse gas emissions by 2050. As they rely on batteries for power, engineers are continuously exploring battery development to increase efficiency © MikesPhotos/Pixabay

REPLACING THE BATTERIES

With governments and businesses committing to net zero and eliminating emissions of carbon dioxide, the pressure is on to replace fossil fuels. Electrification of transport, the largest source of CO_2, is a key part of the UK's approach to this. Batteries will be important in supporting intermittent renewable power sources and providing portable energy. Professor David Greenwood from WMG at the University of Warwick discusses the UK's Faraday Battery Challenge, which supports R&D at all stages of the electrification of transport, from new battery technologies through to disposal and recycling.



The anode, cathode, separator, external circuit, and flow of Li-ions and electrons in a typical Li-ion battery © WMG

Demand for action on climate change has prompted the government to declare a climate emergency and to pledge that the UK will eliminate the country's greenhouse gas emissions by 2050 – an ambition that poses an array of engineering challenges.

With transport making up around 20% of the world's energy consumption, electric vehicles will be essential to achieving net zero. Transport is the largest sector for greenhouse gas emissions in the UK, with road transport accounting for more than 90% of the domestic emissions. In 2018, electric vehicles were just 1.1% of the 2.37 million new cars sold in the UK; 6.2% including petrol–electric hybrids. However, in 2019 sales jumped by 60% with nearly 12,000 sold in the first half of the year and more than 64,000 hybrids and plug-in hybrids sold in the same period. Manufacturing these vehicles requires innovation and engineers are continuously developing new approaches to improve batteries' performance, characterisation and use.

The Faraday Battery Challenge is an important part of the UK's R&D into batteries for electric vehicles. Supported through the Industrial Challenge Strategy Fund, the Faraday Battery Challenge, with a budget of £246 million over four years, covers R&D in all aspects of battery technology (see 'Faraday Battery Challenge'). The £78 million Faraday Institution focuses on fundamental research into battery technologies.

In an electric vehicle, the battery is far more than an energy reservoir. Its array of sensors and electronic systems define almost everything we care about in a car and the 600-kilogram mass of cells underneath the seats is at the heart of the vehicle's design. Battery assembly accounts for half of the cost of building a car, and its capacity governs the driving range. Pressure is on to reduce the cost, and weight, of batteries and to increase their storage capacity.

Most current electric vehicles use a range of hundreds of individually instrumented lithium-ion (Li-ion) cells, the batteries with the highest energy density in commercial use (see 'Lithium-ion batteries: a brief introduction'). These have cathodes that contain cobalt, an expensive raw material, some of which comes from unethical sources. Some suppliers, including Panasonic, the world's largest battery maker, have set themselves the goal of removing cobalt from their products.

FARADAY BATTERY CHALLENGE

The Faraday Battery Challenge is a government investment in research and innovation projects and new facilities to scale up and advance the production, use and recycling of batteries. It aims to lower the UK's carbon emissions and air pollution and create new opportunities and industries.

The project currently focuses on the automotive industry, but its work will also help advance battery development for other applications. The investment of up to £246 million will develop batteries that are cost-effective, high-quality, durable, safe, low-weight, and recyclable.

The investment covers three areas: collaborative research and development projects, which have so far included improving battery lifespan and range as well as the reuse, remanufacture and recycling of batteries at their end-of-life; an £80 million investment to create the UK Battery Industrialisation Centre developed by Coventry and Warwickshire Local Enterprise Partnership, WMG at the University of Warwick and Coventry City Council, which allows companies to quickly develop their capabilities to manufacture batteries and get them to market, scale up and go global; and the Faraday Institution, where academics are working with industry on research, training and analysis into batteries, and helping develop technologies for the future.

FINDING THE ALTERNATIVES

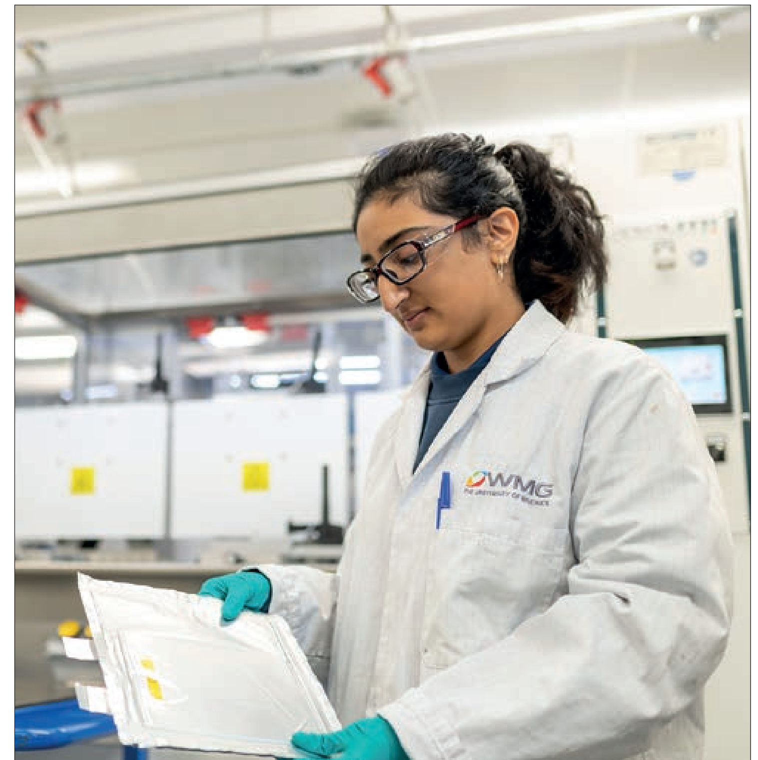
Engineers are researching various alternative battery technologies. One approach is to use so-called solid-state batteries, with solid lithium metal electrodes and solid electrolytes, rather than the flammable organic liquid electrolytes in Li-ion batteries. Mainly used in medical technologies, commercial solid-state batteries could increase a car's driving range, reduce weight and address safety concerns such as flammability and leakage. However, solid-state batteries can fail after repeated charging and discharging at the high current density needed for many consumer applications, preventing their wider adoption.

This failure has been explored by the SOLBALT project at the University of Oxford, which is supported by the Faraday Institution. It has discovered that voids can form and accumulate during charging when current density removes lithium from the interface between the lithium metal and the ceramic electrolyte faster than it can be replenished during discharge. This increases the local current density, leading to dendrite formation (fingers of molten metal that form during battery charging) and battery failure. To prevent dendrite formation, cells need to be charged and discharged below the critical current density at which voids start to form.

As well as these newer technologies, researchers are investigating new uses for older battery technologies. Sodium-ion batteries were developed at the same time as Li-ion batteries and work in the same way, with sodium compounds instead of lithium compounds. However, sodium ions are larger than lithium ions, so the batteries have naturally lower energy density, which limits commercial interest.

One advantage of sodium-ion batteries is that they operate at lower voltages than Li-ion. This means that aluminium can be used in place of copper for the anode current collector without it degrading electrochemically at low states of charge. This lower voltage is also why the electrolytes are cheaper. This makes sodium-ion batteries a viable alternative to lead-acid batteries in scooters, e-bikes and even e-rickshaws, where energy density is less important than cost. Faradion, established in 2011 in Sheffield as the world's first commercial sodium-ion battery maker, demonstrated the world's first sodium-ion e-bike in 2015. Its current prototype cells have an energy density of 140 watt-hours per kilogram (Wh/kg), more than three times the capacity of lead-acid batteries. These batteries can also be a drop-in replacement for lead-acid batteries, offering greater range and faster charging at a similar cost. As battery charging networks develop, sodium-ion batteries could become a solution for passenger vehicles: recent research has shown that sodium-ion batteries can be fully charged in just 20 minutes, which would allow brief 'refuelling' stops and longer operation time.

Lithium-sulphur (Li-S) batteries are also becoming attractive. The theoretical energy density of a Li-S cell is 2,510 Wh/kg, far higher than the 600 Wh/kg or so for Li-ion batteries. Alongside the energy advantages of Li-S cells, sulphur is easy to source and is non-toxic, making it an environmentally friendly



A researcher at WMG works on new battery pouch cell technology
© ERA commercial photography. Photo by Alex Wilkinson Media

LITHIUM-ION BATTERIES: A BRIEF INTRODUCTION

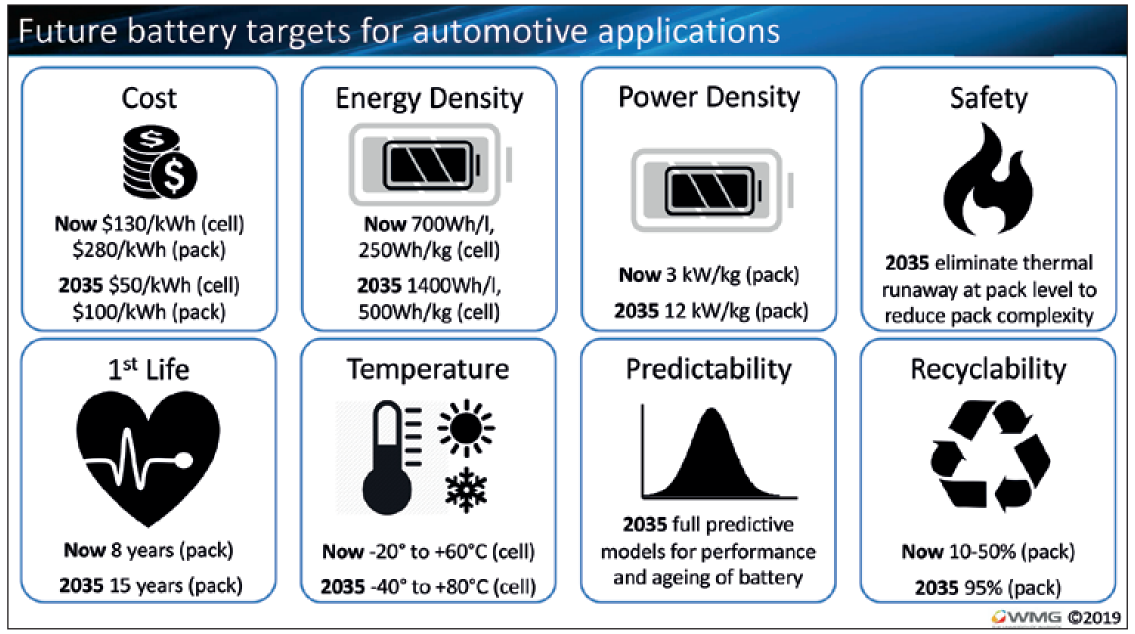
There are many types of lithium-ion (Li-ion) battery, but all are made up of cells: a positive electrode, a negative electrode and an electrolyte. When the battery is charging, lithium ions from the positive electrode move through the electrolyte to the negative electrode. When the battery supplies power, lithium ions move back to the positive electrode. In both cases, electrons flow in the opposite direction to the ions, around the external circuit.

Lithium is an extremely light metal with significant electrochemical potential and energy density for its weight, which made it a subject for battery research from the 1910s to the 1970s when the first non-rechargeable lithium batteries were produced. Unfortunately, lithium's instability made it unsuitable for recharging as dendrites would form and penetrate the separating barrier between the electrodes, causing an electrical short and rapid increase in temperature. As a result, in the late 1970s and early 1980s, researchers investigated compounds such as lithium cobalt oxide and carbon for the electrodes, leading to the development of today's Li-ion batteries. These progressive advances in technology led to John Goodenough, M. Stanley Whittingham and Akira Yoshino winning the 2019 Nobel Prize for chemistry.

Modern Li-ion batteries offer a high cell voltage, are lightweight and can be recharged repeatedly without losing as much capacity as older batteries. This makes them a preferred power source for energy hungry and mobile applications from smartphones to electric cars.

alternative to Li-ion cathodes. However, these advantages also present challenges. Li-S cells have a relatively short cycle life. This is in part because the lithium anode reacts with organic solvents, which, over time, can cause a decline in charging efficiency and a reduction in discharge capacity. Much of the research on Li-S batteries has focused on protecting the anode, which would improve their cycle life significantly.

Li-S has a lower volumetric energy storage density than Li-ion, so Li-S cells will be lighter, but they are also likely to be larger. While this might rule them out for some commercial uses such as cars, they may be more suitable for high altitude and long-range aerospace applications. UK-based Oxis Energy has worked with Bye Aerospace on electrifying piston and turboprop aircraft for regional flight transportation. The company has also investigated possible marine applications. The company, which develops Li-S batteries for a range of industries, is working with the National Oceanography Centre to develop a Li-S battery that can power autonomous marine vehicles at depths of more than 6,000 metres. Through the Revolutionary Electric Vehicle Battery project, funded by InnovateUK, Oxis also worked with Imperial College London, Cranfield University and engineering company Ricardo to develop a 400 Wh/kg cell for a battery electric vehicle, with plans to produce a 500 Wh/kg cell later this year and ambitions to reach 600 Wh/kg.



RESPONDING TO NEED

The variety of battery technologies available and in development suggests that the future of electric vehicles doesn't stop with cars. There is the potential to reengineer aircraft, commercial vehicles and public transport, and to develop batteries to meet each vehicle's needs.

Formula E car racing has been a high-profile success story for battery development. Williams Advanced Engineering, a part of the Formula 1 car company, developed the first battery packs for Formula E. When first launched in 2013, Formula E cars could not complete a race, meaning that drivers had to switch cars mid-event to go the distance. Battery technology progress means that cars can now complete the race. The latest Formula E batteries, developed by Atieva, a part of Lucid Motors, have cells specifically chosen for their race performance, built in a unique trapezium design to fit maximum power inside the car. They contain software that allows the battery pack to perform for the duration of the racing season with no significant degradation.

The emphasis on performance and improved power in racing cars has also helped innovation in aerospace, where the goal is to develop all-electric fixed-wing commercial flights. Rolls-Royce's research programme Accelerating the Electrification of Flight aims to develop the fastest all-electric plane in history to break the current 466 kph world record. The single-seater plane, powered by what Rolls-Royce dubs the "the world's most energy-dense flying battery pack", would have enough energy to fly from London to Paris. Taking inspiration from the successes of Formula E batteries in reducing weight, the team used lightweight materials to cut the plane's packaging-to-battery cell weight ratio in half when compared to an electric car, as well as building in a bespoke liquid cooling system to regulate the heat of the battery cells. The aircraft has three 72 kWh batteries, combining 18,000 Li-ion battery cells, packaged for maximum lightness.

Maximising energy density and minimising weight are essential to high performance road and passenger aerospace vehicles, but in other fields batteries need different qualities that can bring added benefits. For example, when JCB began designing an all-electric mini-excavator it became clear that the vehicle would be ideal for work indoors, in tunnels or even underground, as there would be no need to extract toxic combustion fumes. It produces just a fifth of the noise of a traditional diesel engine model, an advantage for work in busy cities.

Electrifying transport in pursuit of net zero requires more than just finding more efficient and economical ways to store electricity. Engineers also need to find ways to make electric vehicles fit into our lives. While new technologies and applications are important, existing technology needs improvements, such as quicker charging. The ability to fast-charge car batteries is essential in reducing the fear that a car's batteries will run flat in the middle of a journey. However, current fast-charging technology can produce triple the heat energy of slower charging. Li-ion batteries operate best inside a relatively narrow temperature range, roughly 15°C to 35°C: too cold and they charge too slowly, while excessive heat can degrade performance and can accelerate battery ageing. Good thermal management is the key to better battery performance, more range on a single charge and a longer cell life.

In another programme funded as a part of the Faraday Challenge, research is under way to cool batteries in use. The I-Co Bat research programme is developing a battery pack concept that uses a biodegradable cooling fluid, MIVOLT, to immersion-cool the battery. MIVOLT is developed from dielectric fluids currently used to cool and insulate transformers in wind turbines and high-speed trains. The batteries are immersed in coolant to reduce heat, improve charging time, and lengthen battery life. A research collaboration between WMG at the University of Warwick, Manchester-based M&I Materials, which has more than 40 years' experience in manufacturing products for electrical insulation, and electric vehicle battery pack and management specialists at Ricardo, is aiming to validate and commercialise this new form of battery cooling.

Whether developing sustainable battery technologies, finding new uses for established battery types, improving the performance of existing batteries or giving new life to old batteries, UK engineers are transforming the way we power our world. In the near future, batteries will power planes, ships, construction vehicles, homes and cars, helping deliver a zero-carbon economy and a cleaner world.

RECYCLING

Batteries from electric vehicles (EVs) have a lifespan of around ten years before they need replacing. An EV battery reaches the end of its automotive life when its capacity falls to 80% of a new battery.

The Global Battery Alliance, a World Economic Forum initiative to accelerate and scale up action towards an innovative and sustainable battery supply chain, estimates that there will be 11 million tonnes of spent Li-ion batteries globally by 2030. The good news is that various recycling methods are already in commercial use and could deal with the pending landslide of used car batteries.

The batteries in most EVs use Li-ion cells, and older hybrids use nickel metal hydride. They rely on metals such as lithium, copper, nickel, manganese, and cobalt to provide energy-dense cells that are relatively small and light. The cell itself – complete with these metals and a highly flammable electrolyte – makes up around 60% of the battery. The casing accounts for 30% while the rest of the package consists of wiring, cooling tubes, busbars, screws, adhesive and embedded electronics, an important part of the control system that monitors the health of each cell and manages the energy flow. Over 90% of the cell can technically be recovered. However, recycling is a commercial activity that involves the reuse of recovered materials. Many companies will only recycle parts that give them a financial return.

Li-ion batteries are covered by the EU's Battery Directive, which stipulates that at least 50% of the entire battery must be recycled. Battery packs are dismantled manually. The plastics and wiring that make up the bulk of the pack around the cell can be recycled along with other similar plastics. This is straightforward and achievable.

The main difficulty is that the valuable metals are embedded in electrodes and surrounded by volatile electrolyte. The electrolyte is a solution of organic carbonates and a conducting salt that is flammable, explosive and highly toxic. Any recycling process must deal with these hazards before the rest of the cell can be recycled. This electrolyte makes battery recycling more hazardous than conventional recycling of plastic and metal. In future, advanced robotics could aid the recovery of battery content, reducing potential harm to human operatives.

To this end, the National Centre for Nuclear Robotics is examining how to build robots to operate in extreme environments. It is working with the Faraday Institution to produce robots using artificial intelligence to remove batteries from vehicles for final recycling. The Faraday Institution's ReLiB project on recycling and reuse of Li-ion batteries sets out to improve the recovery, re-use and recycling of batteries, with the ultimate aim of retaining almost 100% of the battery components within the automotive sector.

The first step in improving the efficiency of battery recycling is learning how to accurately assess the state of a battery before it is removed. In this way, the batteries can be safely transported to the relevant recycling or reuse facility. Some companies use high temperature processing to destroy the electrolyte and then treat the toxic gases generated. This approach, called pyrometallurgy, involves processing batteries in a furnace. Other recyclers use specialist technologies, such as shredders, to cut open cells in an inert atmosphere and then treat or capture the electrolyte and electrode materials. Once this is done, the remaining battery components can be recycled in the usual way.

The cathodes in batteries contain lithium and cobalt, valuable metals that can be extracted for reuse in new batteries. In the process the metals lose none of their electrochemical properties, so a battery made with recycled metal is just as efficient as one made with freshly mined metals. Recapturing these metals is the most important aspect of battery recycling. The metals, particularly cobalt, are expensive and mining them is resource-heavy and environmentally damaging.

The ability to recycle batteries efficiently makes economic, environmental and moral sense, which is why many manufacturers are beginning to focus on the idea of 'circular economy' battery manufacture and reuse.

Copy written by Vicky Parrott, freelance journalist

BIOGRAPHY

Professor David Greenwood leads the Advanced Propulsion Systems team at WMG and also provides academic leadership for the development of R&D activities within the National Automotive Innovation Centre. He is a board member at the Low Carbon Vehicle Partnership and a member of the Automotive Council Technology Group.

Leigh-Ann Russell FREng manages BP's upstream supply chain, helping to procure and deliver all the company's goods and services in a safe and ethical manner

A VITAL LINK IN THE CHAIN

As Head of Upstream Supply Chain at BP, Leigh-Ann Russell FREng is responsible for a team of 900 and a budget of $20 billion a year, a role that came to the fore during the coronavirus pandemic. Her position builds on skills developed as a completion engineer, working on drilling operations in the harsh North Sea offshore operating environment. She explained to Michael Kenward OBE how supply chains are important in the pursuit of net zero.

It was a close shave for Leigh-Ann Russell FREng. Her parents were delighted when she landed what seemed like an ideal first job for a 16-year-old. "You can imagine: on a council estate, getting a job in the Bank of Scotland in Aberdeen, a really prestigious bank. It was just everything to my parents." Six months into her 'dream job', Russell received "surprisingly good" exam results and had second thoughts about how she would spend her working life. She told her family that she wanted to ditch the secure bank job and to go to university. "They thought I was ridiculous," Russell laughs. "Then I told them that I wanted to study engineering. They thought that was even more foolish."

As Russell recounts it, the family response was: "Why would you want to give up your job in the bank to go to university?" No one else in the family had gone to university. This was followed by "engineering is not for women". Her parents may have been shocked at first, she says, but no one tried to stop her. "I never heard the words 'you can't do that'," she adds. "Eventually my dad said, 'well at least I will have somebody who can fix my car for free in the future. You should go for it'."

When it came to choosing a degree course, Russell made a pragmatic choice. "I looked at all the options available for me and picked engineering because it wasn't narrow. Engineering allowed me to keep my options open." The fact that careers in STEM paid well also helped sway her. "When you come from an environment like I grew up in, being able to lift yourself out of poverty and help your extended family financially has been one of the most wonderful things."

Russell's move into engineering started with a degree at the University of Aberdeen. In the 1990s, the city had two main industries: fishing and oil, a sector with engineering at its core. The university was also a centre for research and training in oil and gas. With her degree completed, Russell went to Schlumberger, a leading player in oil-field services and equipment, where she completed a graduate training programme while working on field operations. There followed a sequence of increasingly senior engineering roles before she joined BP in 2006, at the lower end of the engineering ladder.

When she was working in the North Sea with BP, Russell discovered similarities between a job in oil and gas and fishing. "I saw my grandfather, who was a cook on a fishing boat, and heard his stories. It didn't seem very appealing, being out in the elements on the North Sea, being hit by waves. Then I ended up going into oil and gas where I was off on platforms in the middle of the North Sea being hit by waves," Russell says with a laugh. "But at least we had really nice survival suits and warm clothing."

Russell worked as a completion engineer on various projects. "The drillers make a hole and find oil and gas. The completion engineers remove it from the ground as safely and efficiently as possible." Russell rose through the ranks, spending five years leading engineering, operations, process safety, and strategy and performance for BP's $5 billion drilling business, at a difficult time for the oil industry. After 20 years at the heavy engineering end of the oil and gas business, there was a dramatic change in Russell's role.

MOVING UPSTREAM

In 2018, Russell took charge of the supply chain for BP's upstream operations, which finds oil and gas and puts in place the infrastructure needed to bring it to the surface. Asked what the Head of Upstream Supply Chain does, Russell says "we procure and deliver all our company's goods and services in a safe, ethical and reliable manner". This means that she has responsibility for $20 billion a year and a staff of 900 around the globe. "I have learned a lot in this role," she says, "stepping out of mainstream engineering after two decades. It is really a very commercial role, but also a technical role, because you are buying products and services that supply a high-hazard industry."

Engineers don't usually end up in charge of supply chains, Russell admits, but they may now be much more familiar with the role in the wake of the COVID-19 pandemic and all the talk of laying hands on personal protective equipment (PPE). In Russell's case, she suddenly found herself reading up on PPE. "Initially our supply chain was engaged heavily in purchasing equipment for emergency services." As it swung into action, BP asked her to lead an executive steering committee looking at the company's response to COVID-19. "Supply chains typically would not be sitting at the emergency response committee in oil and gas companies," she explains. "But it was recognised that we could play a vital role on many fronts."

BP's supply chain teams around the world moved to provide local support. UK efforts involved buying masks for the NHS, for example. Then there was the challenge of maintaining security of supply in BP's oil and gas operations, with factories in China and Italy closing down at the start of the pandemic. Throw into this a chaotic energy market and "it is a brutal environment for oil and gas companies", as Russell puts it. "It has had an even harder effect on our supply chain than it had on oil and gas companies themselves."

Russell is full of praise for the response to the pandemic of the far-flung network of

BP people, often working from home in difficult conditions. "I am really proud of what our company, and also the supply chain, has been able to do across those multiple fronts."

CLEAN ENERGY

There is no hint that Russell feels that she has joined a 20th century industry that is on its way out. Sure, climate change looms large over fossil fuels, but that does not mean the end of the energy industry. "When you look at the energy transition, and what the world needs for energy, we have an even bigger role to play in society. We now have to continue to provide that product – heat, light and energy – but we have to do it in a cleaner way."

One sign of the revolution that has hit the fossil fuel industry came earlier this year when BP's new CEO, Bernard Looney FREng, unveiled the company's ambition "to become a net zero company by 2050 or sooner, and help the world get to net zero". Eliminating greenhouse gas emissions will not mean an end to oil and gas, she insists. "We still have a product that is needed in society," Russell explains. But it has to be produced and consumed in a carbon neutral way. Engineers will need all their skills to make that happen. For example, reducing emissions means "making sure that gas stays within the pipeline and that we detect leaks as quickly as possible". BP now deploys drones, crawlers and other innovative technologies to make the product cleaner. "While we are doing an amazing job in getting the renewable side of our business going and investing and creating new businesses, reducing our carbon emissions from our existing businesses becomes really critical as well."

This draws Russell into explaining new areas of engineering and the symbiosis of information technology and 'hard hat' engineering in oil and gas operations. When

Leigh-Ann speaking at a BP networking event © BP

she joined the industry, it was beginning to deploy acoustic technology. As they drill a well, engineers run an optical fibre along the pipeline. "This is thousands of kilometres under the seabed, with wet connections between different pieces of pipe." This is in a high-temperature, high-pressure environment. The completion engineers then use sensors and the fibre optic link to listen to oil and gas as it comes out of the ground. "We have built an algorithm that tells us what is happening along the length of this wellbore. It is hugely reliable." The system reveals when and where oil and gas are coming from and if water or sand enter the pipe, which can damage an oil and gas well. Knowing what is going on, the operations engineers can go into the well and intervene in what is happening. "This is all done in a tiny piece of fibre with a really amazing algorithm," says Russell. "This is BP proprietary technology. Our engineers were the ones who did this. It is just phenomenal."

Technology like this will be essential in the pursuit of net zero. "That data allows us to massively optimise the production that we get from that well. Drilling a well takes a lot of money, but it also has an impact on the environment." Optimising how much oil and gas reservoirs deliver means fewer wells can be drilled. This technology can also help optimise oil and gas production on a larger scale. "If you bolt on to that a data platform that has all of the data from all of our wells around the world, you can start to play all kinds of different games with optimising production."

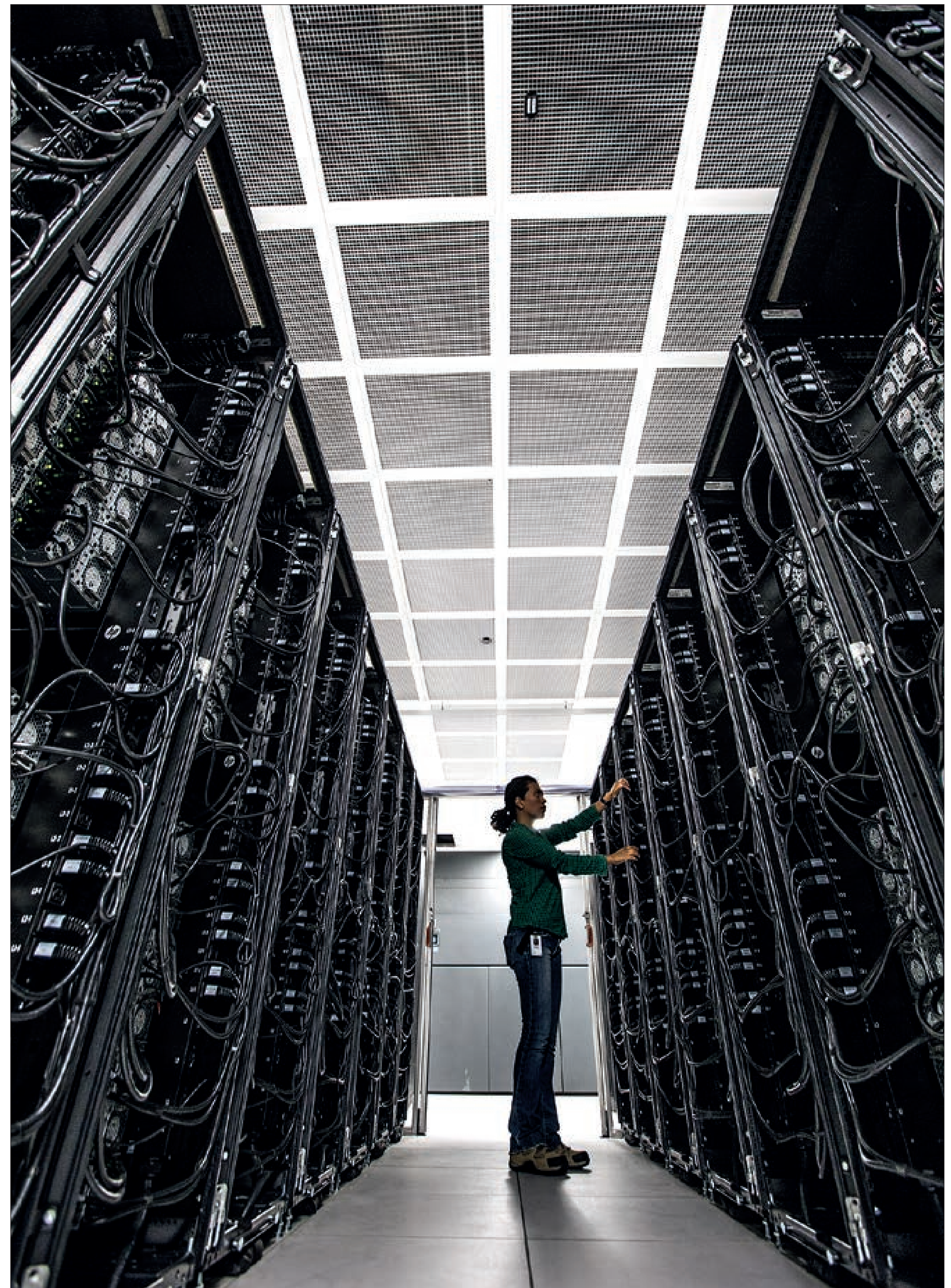
THINK LIKE AN ENGINEER

Russell is a great believer in assembling teams with diverse skills. As a 'digital native', educated in an era when computing and IT were a constant presence, she can see the benefits of blending it with the rest of engineering. "We have had a lot of digital talent join the organisation. But there is also a massive role in upskilling our individuals to be able to do both."

As Russell sees it the key is giving people digital skills. People don't need to be data scientists, she insists, to be able to exploit IT. "Some of our engineers are teaching themselves coding: that amazing combination of digital skills and engineering expertise has led to some quite phenomenal projects."

What matters, says Russell, is the engineer's way of thinking. "Adapting to situations is at the heart of being an engineer and what we are inherently good at. Give us a problem and we will solve it. There are lots of problems in the world today."

What does an engineer make of the new world of running supply chains? "I discovered that having supply chain professionals and engineers working together to get the right outcome is really important. The supply chain professional might not really understand the technical side of things, but most of our engineers don't have that commercial skill." One reason for dropping an engineer into supply chain management is that it prompts the business's engineers to think about how their decisions affect their counterparts in their suppliers. "We work with companies that are absolutely amazingly world class," says Russell. "We have gone to some of our partners and said 'We keep telling you how to do this, is there a better way?'"



Data analysis is among the newer forms of technology that BP is employing to ensure its operations remain efficient © BP

Supply chains will also be crucial in BP's pursuit of net zero. "It is impossible to achieve what we want to do without bringing our supply chain along," says Russell. Around 60% of BP's spending goes into the supply chain; it also accounts for around 80% of the people employed on the company's behalf. "If you don't understand the impact that your supply chain has on the environment, then you are just not going to be successful at all." In turn, suppliers must also take the message onboard. It is BP's job, she says, to get suppliers to understand where they can play a part.

Working in supply chains has certainly taken Russell in interesting directions. Another lockdown activity involved calls to the chief operating officer of a major supermarket, which is one of the UK's biggest supply chains. "The problems that we have as engineers are similar whatever sector you are in right now." BP also has a partnership with Amazon Business Services, "looking at a different way of buying products that is more efficient and easier for our internal customers to use", she explains. "If you had told me ten years ago that I would be working on projects with Amazon I would not have made that connection."

Russell might also have been surprised that an oil company can also benefit from talking to medics. In another lockdown activity, Russell has been talking to someone she mentors in the medical sector. "She was telling me about digital advances in the medical sector that are happening right now as hospitals strive to work differently under COVID-19. I learned about a few things that we might be able to do in oil and gas because of that conversation."

This line of thinking takes Russell into a key area for her, the importance of diversity

Refinery engineering technicians at BP. Leigh-Ann Russell emphasises the importance of ensuring that the engineering pipeline has enough diversity in it to change the demographics of engineering © BP

in general. Her line is that teams need diversity. "Engineers don't know everything," she confides. "The things you can learn from different skillsets and different mindsets just takes a business to a different level." A couple of decades ago, she continues, whatever the engineers said went and engineers got all the management jobs. "I don't think that is healthy in terms of growing businesses."

DIVERSE TEAMS

Russell is passionate about having a diversity of people working in the organisation. Clearly having a good mixture of women in a team is high on her agenda, but beyond that teams perform better if they bring together people with different skills and ways of thinking. "That isn't necessarily about being female; someone might have a different ethnic background, or it could be someone who comes from a council estate versus Eton." However, the role of women in engineering is clearly high in her thinking.

"Some women think it is not a woman's problem, it's a society problem. I 100% agree," she stresses. "Women are not going to fix diversity. Men are going to fix diversity because they hold the positions of power. I get that." Her reason for taking a public stand is that "it is just about seeing somebody who looks like you".

In Russell's case, few people share her background. "Growing up on a council estate in the north-east of Scotland, becoming an engineer was a risky option for me personally." She is determined to show other young people that it is possible. "I want young women to see that you can wear a dress and heels, and you can still be an engineer because it is a wonderful career opportunity. I have absolutely loved every single day of my – not every single day, that's not true – but I love my job."

Russell has risen to the upper echelons of engineering and wants to encourage others to follow in her footsteps. Again, the challenge is something of a supply chain imperative. But without enough women or other minorities in the pipeline, she says that the demographics will never change.

It is also a national imperative, says Russell. "We will not be successful in this country without engineers. We will not be successful as engineers unless we bring in young talent. I worry about the dearth of talent that we will attract unless we make a concerted effort. It must be diverse talent. We know that having that mix of men and women and a mix of backgrounds is what makes companies really successful. That doesn't need to be debated any more. There are a million studies that show that companies with diversity are stronger financially, less likely to go bust. We don't need to keep telling people that."

Russell cites BP as an example of what can be done to encourage diversity. "Nearly 30% of our senior leaders are women: 25% of our most senior executives are women. In an oil and gas company I think that is a radical shift." The challenge now is to ensure that the global pandemic does not bring an end to recent progress. "I do worry that in an economic downturn we just forget. We are not taking our foot off the pedal [at BP] but we need to make sure that the supply chain doesn't. It is not a 'nice to have'. Diversity is what is going to make our country and company successful."

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, **1975**. BSc Engineering, University of Aberdeen, **1997**. Joined BP, **2006**. *Houston Business Journal* 40 under 40, **2014**. Head of Upstream Supply Chain, **2018**. Fellow of the Energy Institute, **2018**. Fellow of the Royal Academy of Engineering, **2019**.

ANOTHER BRICK IN THE WALL

With natural resources running low, Scottish engineers have created a brick that uses more than 90% recycled building materials.

In 2019, the UK made two billion bricks but still needed to import an additional 600 million. The UK government's new house-building targets are increasing demand for new building materials, but many construction products are unsustainable and more than 30% of landfill waste comes from the construction and demolition of buildings.

Kenoteq, a Heriot-Watt University spinout, has used this construction and demolition waste to create a sustainable building product that is formed of over 90% recycled materials. The K-Briq looks and behaves like a clay brick and weighs the same but offers better insulation properties. The bricks don't need to be fired, so produce just 10% of the carbon emissions that standard fired bricks create. At the end of their life, the bricks can be ground back down to create new K-Briqs, beginning the cycle again.

K-briqs can be made in a range of colours by adding recycled pigments to the mix

The company arose from a partnership between Dr Sam Chapman, a structural engineer with an interest in carbon footprinting and engineering professor Gabriela Medero. Professor Medero had been thinking about how construction materials could be reused for more than 10 years, with an aim to create a more circular economy in construction. Having just completed a PhD in carbon assessment of wind power, Dr Chapman stepped in to carry out a carbon assessment of the potential product and looked at the lifecycle carbon emissions. The pair then applied for a Royal Academy of Engineering Enterprise Fellowship with their prototype to develop and support commercialisation of the product.

Kenoteq set up its pilot production onsite with a waste handling company. Kenoteq collects inert demolition waste, for example old bricks, rubble and gypsum plaster, before mixing the waste with its binder and compressing it into bricks. Recycled pigments can also be added to produce bricks in any colour. By partnering with companies that already deal with construction waste, Kenoteq ensures that it is not adding trucks to the road – the heavy waste comes to the site anyway, and empty trucks going to collect waste from building sites are ideally suited to deposit the finished product in a place that requires it.

The regulatory process involved in bringing a new product to market is understandably extensive and challenging. The main certifying bodies have been guiding the team through the certification process, and the team has conducted extensive testing and development at Heriot-Watt University to ensure that the bricks could meet safety standards.

K-Briq modules were to due to make their debut in this year's Serpentine Pavilion – an annual architectural event. The Pavilion, designed by South African architectural studio Counterspace, is using custom-sized K-Briq modules, allowing Kenoteq to test and experiment with new colours and textures. However, due to the COVID-19 pandemic, the opening has been postponed until 2021.

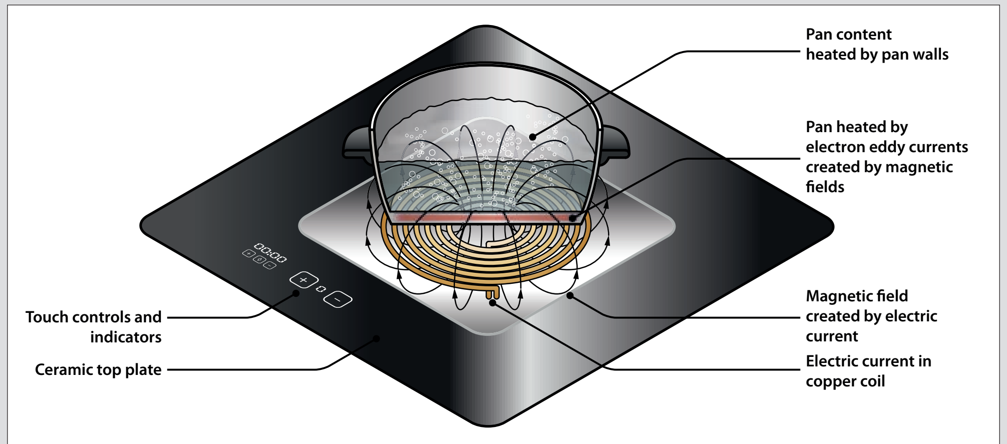
By the end of the year, Kenoteq is aiming to scale-up its manufacturing capacity to three million bricks a year. It is also aiming to create a brick out of 100% recycled material, and exploring options to expand its product range to other building materials.

For more information, visit **www.kenoteq.com** or **@Kenoteq**

HOW DOES THAT WORK?

INDUCTION HOBS

In an induction hob, a coil of copper wire is placed under a cooking pot and an alternating electric current passed through it. The resulting oscillating magnetic field wirelessly induces an electrical current in the pot, warming it up and cooking the food inside.



Copper coils inside an induction hob heat the pan, rather than the surface of the hob, through a magnetic field created by an alternating electrical current © Shutterstock

Kitchens come in all shapes and sizes but you almost certainly have some sort of cooker at home. If you have a gas or electric cooker, it's probably quite obvious how it heats your food. A gas cooker creates a flame and the heat from that flame is transferred to the pan that you've placed on top of it, heating the food inside. With an electric cooker, the hob itself heats up and again you have a transfer of heat from the hob to the pan. In both cases, the hob itself gets very hot and this heat is then used to heat the pan. But what about induction cookers, which heat the pan directly rather than the hob?

An induction cooker has a ceramic surface, topped with glass, beneath which are four coils of copper – one for each hob. When a hob is turned on, electricity runs through the coil and this generates an electric field. The French physicist Ampere discovered that whenever and wherever you have an electric field, you also have a magnetic field, and that you cannot have one without the other. At this point no heat is being generated because on induction cookers, the pan generates the heat rather than the hob. It relies on induction, a concept discovered by Michael Faraday FRS. He found that when he wrapped two wires close together and sent an alternating electrical current through one of them, an electrical effect was measured in the second wire. This is what is happening with an induction cooker.

When you put an iron-based pan on top of the glass, the magnetic field generates electric fields in the iron in the bottom of the pan. Since iron is not a very good conductor of electricity, it heats up and this is where the heat that cooks the food comes from. Although switched on, the hob will stay cool until a pan is placed on top; however, the pan does then heat up the hob and it will take time to cool after the pan is removed. It only works with pans that have iron in them; pans made of copper, for example, will not heat up because copper conducts electricity too well. The easiest way to check if a pan contains iron is to use a magnet, which will stick to the pan if it contains iron.

Safety tests have been carried out to see if the magnetic field has any impact on items that will potentially be nearby, such as rings on fingers and pacemakers. The British Heart Foundation advises that people with pacemakers should keep a distance of at least 60 centimetres from an induction hob while it is on, as it can interfere with the device, or avoid them completely.

Because the heat comes from the pan itself rather than the stove, heat is evenly spread throughout the pan making cooking more efficient – induction hobs can heat a pan of water to boiling point in half the time of a gas-powered one. The lack of heat on the hob itself means that food doesn't burn onto the surface when it boils over, so the surface is easy to clean.

BIOGRAPHY
Rhys Phillips is an ambassador for the Queen Elizabeth Prize for Engineering (QEPrize). He has spent over 10 years working in electromagnetics research topics at Airbus and is also Senior Vice President of Public Relations for European Young Engineers. Follow him on Twitter @rhys_phillips

To learn more about the engineering marvels hidden in your home, watch Rhys discuss induction hobs and other engineers' videos on Twitter at @QEPrize. The videos are part of the QEPrize's #EngineeringInspiration video campaign, celebrating the launch of the 2021 QEPrize nominations.

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