ingenia

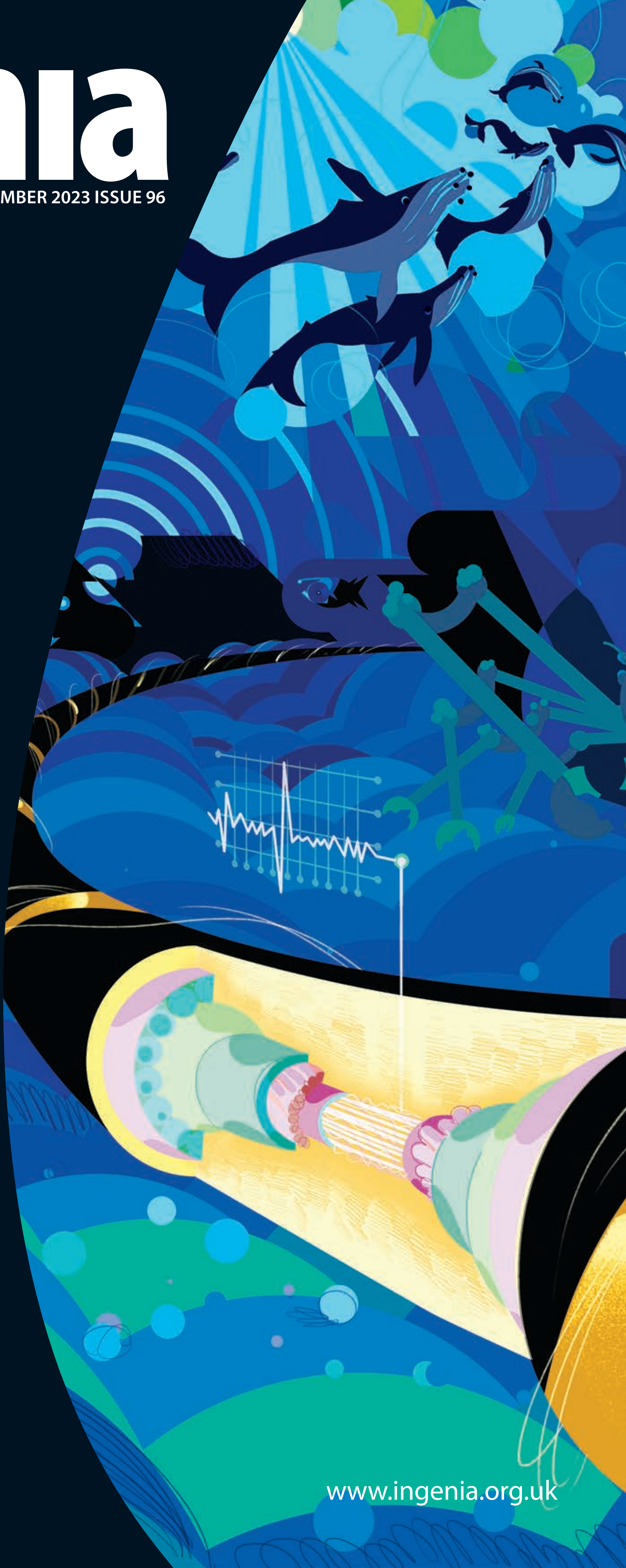
SEPTEMBER 2023 ISSUE 96

PROTECTING THE COAST

AWARD-WINNING BRIDGE DESIGN

CONSERVING HISTORIC STRUCTURES

SUPER-FAST SUBSEA CABLES



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Front cover
Artist's impression of a subsea telecommunications cable
© Benjamin Lyon

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WELCOME

As society looks to reverse or slow down the effects of climate change, engineers are playing a key role.

In this issue in particular, we look at the ways in which engineers are both monitoring and devising solutions to lessen the impacts of waves, wind and storms. Coastal erosion is a significant problem that is increasing because of climate change. On page 20, we discover how engineers are protecting coastlines and coastal communities from the threat of erosion.

Meanwhile, as many of the UK's rock-mounted, offshore lighthouses, which are continually exposed to stormy weather, approach their 200th anniversaries, a collaborative research project has assessed their integrity and future resilience (page 24).

Staying with the sea, engineers are developing faster subsea telecommunication cables with higher capacities to meet the world's increasing appetite for data. And the sensors in these cables are also being employed for other tasks, such as tracking the migration of whales or predicting earthquakes (page 10).

In a bid to reach net zero, Ceres Power has developed a MacRobert Award-winning technology to scale up creation of green hydrogen – read about the company's innovative cleantech on page 34 then turn the page to find out just how electrolysers make green hydrogen in How does that work?

And sustainability is high on the agenda for Transport for London's Head of Engineering, Kuldeep Gharatya FREng. On page 29, read how the organisation is bringing 'climate thinking' into its systems engineering approach.

As always, please let us know what you think of the issue at ingenia@raeng.org.uk or via Twitter using #IngeniaMag. Also, don't forget that you can subscribe to our e-newsletter via our website.

Faith Wainwright

Faith Wainwright MBE FREng
Editor-in-Chief

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IN BRIEF

CLEAN ENERGY PIONEER WINS MACROBERT AWARD

Left: Academy President Professor Sir Jim McDonald FREng FRSE and HRH Princess Royal with the Ceres Power team at the Awards Dinner. Right: The winners of the Princess Royal Silver Medals

In July, the Royal Academy of Engineering hosted its annual Awards Dinner to celebrate engineers at all stages of their careers and recognise outstanding achievements and innovations from the UK's engineering community.

The highlight of the evening was the presentation of the 2023 MacRobert Award – the UK's most prestigious award for innovation in UK engineering – to Ceres Power for its pioneering clean energy technology. Ceres' groundbreaking fuel cell technology promises to make a major contribution to decarbonising at the scale and pace required to save the planet.

Made from common, inexpensive materials, the fuel cell impressed the judges with its reversible technology. In one direction, the cell generates electricity, and in reverse, it produces low-cost green hydrogen – both at high efficiencies. Thanks to Ceres' licensing model, the company has established partnerships with companies such as Bosch, Doosan and Weichai. It has 250 megawatts of capacity set to come on stream in 2024, which could power half a million homes.

The Academy's Royal Fellow, HRH The Princess Royal, and Academy President Professor Sir Jim McDonald FREng FRSE presented the winning team behind the Ceres SteelCell with the MacRobert Award gold medal and a £50,000 prize. The two other finalists were nPlan, whose AI technology saves millions on construction projects by accurately assessing delays, and Paragraf, which has produced the first commercial use of graphene in electronic devices.

The MacRobert Award was one of several prestigious accolades presented at the Awards Dinner. This year's Major Project Award for Sustainability was presented to Buro Happold for its role in the restoration of the Grade II* listed Battersea Power Station. The Buro Happold team developed a unique understanding of the building's fabric and structural behaviour that was vital in maximising sustainable reuse of the structure and materials. Five exceptional young engineers were named RAEng Engineers Trust Young Engineer of the Year. Professor Harrison Steele, an associate professor at the University of Oxford and inventor of the Chi.Bio robotic bioreactor used in the biotech industry, also received the Sir George Macfarlane Medal. The other winners were Dr Jiaqi Chu, Principal Researcher at Microsoft Research; Joseph Harvey, Offshore 400kV Senior Authorised Person at SSE Renewables; Mihir Sheth, CEO of Inspiritus Health; and Dr Fiona Walport, Research Fellow at Imperial College London.

This year's Princess Royal Silver Medals were awarded to four of the UK's leading innovators: Dr Saritha Arunkumar, IBM Public Cloud WorldWide Technical Leader for Security; Joel Gibbard MBE and Samantha Payne MBE, respectively CEO and COO of Open Bionics; and James Roberts, Co-Founder and CEO of mOm Incubators. Meanwhile, Ruth Amos, Co-Founder of popular YouTube channel, Kids Invent Stuff, received the 2023 Rooke Award for public promotion of engineering. Ruth is an award-winning British inventor, presenter and speaker whose work engages children with STEAM (science, technology, engineering, arts, and maths).

AFRICA PRIZE AWARDED TO TWO INNOVATORS

The two joint winners of the 2023 Africa Prize for Engineering Innovation: Anatoli Kirigwajjo, Co-Founder of a Ugandan affordable security startup (left), with Edmund Wessels, inventor of a portable gynaecological device designed to improve women's access to quality healthcare in remote areas (right)

On 6 July, two innovators were named winners of the Africa Prize for Engineering Innovation for the first time, for technologies in affordable security and women's health.

Ugandan electrical engineer Anatoli Kirigwajjo won with his community 'panic button' inspired by traditional African warning drums, while South African biomedical engineer Edmund Wessels won with his portable gynaecology device, designed to increase access to reproductive healthcare for women in remote areas.

Anatoli and his co-founders developed YUNGA, a local digital security network that connects neighbours to each other and police within a 20-kilometre radius through a physical device, smartphone app or SMS service, providing low-cost security. The team is aiming to connect 32,000 households across Uganda in the next two years, and say that winning the Africa Prize will give their business exposure in new markets across Africa.

Edmund's FlexiGyn battery-powered, handheld device enables gynaecologists to diagnose and treat women's uterine problems without anaesthetic or expensive equipment. It aims to increase women's access to reproductive healthcare, particularly in remote areas. Edmund and his co-founder are also developing software solutions to help integrate Flexigyn with existing medical practice systems to further enhance quality of care.

The remaining 11 innovators from the 2023 shortlist competed for the One to Watch Prize by pitching to a live audience, who voted for the innovation with the most potential for impact. Tolulope Olukokun was selected as the winner, receiving £5,000. Tolulope was recognised for his electric cargo bike with a battery-powered fridge, designed to help Nigeria's smallholder farmers get fresh food crops to market. The profiles and pitch decks of the 15 engineers comprising the 2023 cohort can be viewed at **africaprize.raeng.org.uk/cohort-2023**

REPORT HIGHLIGHTS ROLE OF ENGINEERING IN UK ECONOMY

In July, the Royal Academy of Engineering published, *Engineering Economy & Place*, a deep dive into engineering's role in the UK economy. The report intends to inform policymakers about how to share the benefits of engineering across society and help the UK to achieve its engineering, science and technology ambitions.

Produced in collaboration with place-focused consultancy Metro Dynamics, the report revealed that engineering represents 32% of total national economic output and 26% of jobs nationally. However, it warns that, without action to implement a place-based approach to engineering policy, the UK risks hindering its economic growth.

The new data paints a detailed picture of the differences between engineering in different regions and local areas and draws broad conclusions about how to address regional imbalances in engineering's contribution to the UK economy. For example, one recommendation was to improve connections between city centre R&D activity and nearby regions and towns, along with rural areas, to encourage high-value engineering and innovation.

To read more and explore the report's interactive dashboard, visit **raeng.org.uk/eep**

BIO-INSPIRED 'LEAF' DESIGN COULD AID ENERGY TRANSITION

Conceptual structure of a photovoltaic leaf © Dr Gan Huang

Researchers at Imperial College London have discovered that a new nature-inspired leaf design for harvesting solar energy could increase the efficiency of future renewable technologies.

Typical plant leaves are made of different structures that allow them to move water from the plant's roots to its leaves through a process called transpiration. Made using low-cost materials, the photovoltaic (PV) leaf concept mimics the transpiration process, so that water can move, distribute and evaporate. It uses natural fibres to mimic leaf vein bundles while hydrogels simulate sponge cells to remove heat effectively and affordably from solar PV cells.

Researchers carried out a series of experiments that suggest a PV-leaf can generate over 10% more electricity compared to conventional solar panels, which lose up to 70% of the incoming solar energy to the environment.

Dr Gan Huang, Honorary Research Fellow in Imperial College London's Department of Chemical Engineering, and author of the study said: "This innovative design holds tremendous potential for significantly enhancing the performance of solar panels, while also ensuring cost-effectiveness and practicality."

The full study was published in *Nature Communications*.

STUDENT TEAM WINS MOTOR RACING COMPETITION

This year's Formula Student racing car competition has been won by a team from the University of Modena and Reggio Emilia for the second time.

One of the largest student motorsport competitions in Europe, Formula Student celebrated its 25th anniversary at an event held at Silverstone Race Circuit in July. The Italian team from the University of Modena and Reggio Emilia first won in 2019, which is also the last time it competed. Staffordshire University took second place and Oxford Brookes University came third.

The competition, which is run by the Institution of Mechanical Engineers, gives students a real-world challenge to design, build and race single seater cars. These culminate in the finals event held at Silverstone, which combine formal presentations of their work throughout the year with a range of on-track events that demonstrate the capabilities of their car.

For the first time in the competition's history, teams running petrol engines had the chance to run new biofuels offered by Coryton and Motorsport UK, in a bid towards running a more sustainable competition. These were used by a number of combustion entries this year, including the overall winners from Modena who were running an E85 fuel.

The University of Modena and Reggio Emilia winning design © Formula Student

GET INVOLVED IN ENGINEERING

THE TURING LECTURES: WHAT IS GENERATIVE AI?

22 September 2023
The Alan Turing Institute, London, and online
This lecture will delve into the world of generative AI and explore what it is, how it works, its history, and reliability. Professor Mirella Lapata from the University of Edinburgh will present an overview of this exciting – sometimes controversial – and rapidly evolving field.
www.turing.ac.uk/events/turing-lectures-what-generative-ai

NATIONAL ENGINEERING DAY

1 November
The countdown to National Engineering Day has begun! Keep your eyes peeled for a competition that will be launched in early October to encourage everyone to tap into their inner engineer and find those of us with ideas and innovations that could make or are making our daily life more sustainable. This year the Royal Academy of Engineering is teaming up with *Dragon's Den* investor and successful entrepreneur, Deborah Meaden, to launch the 'Everyday Engineering' competition – a four-week national competition to find the UK's kitchen table engineers. From 2 October, the public can enter their ideas and creations, then the public will vote for their favourite sustainable idea or innovation on social media on National Engineering Day. Prizes for the winner include a meeting and advice from Deborah Meaden, mentoring from an engineering entrepreneur and more. To find out more, visit **www.raeng.org.uk/national-engineering-day**

NEW SCIENTIST LIVE

7 to 9 October 2023
ExCel London and online
There's no shortage of talks and exhibitions to get engrossed in at this year's New Scientist Live. In the talks, learn about the role of robots in the future of food production or hear CEO of Stemettes Dr Anne-Marie Imafidon MBE HonFREng discuss careers in STEAM. Meanwhile, meet SPOT the robotic dog, who is exploring hard-to-reach and hazardous areas, or take a ride on a virtual reality rollercoaster. Monday 9 October is a day dedicated to school groups. To book tickets, visit **live.newscientist.com**

ADA LOVELACE DAY LIVE!

10 October 2023
Ri, London, and online
Now in its 15th year, Ada Lovelace Day Live is a global celebration highlighting and honouring the achievements of women in STEM. It is named after Ada Lovelace, the world's first published computer programmer. At this event at the Ri, you can hear from leading women in STEM, including science presenter and comedian Helen Arney, senior software engineer Azza Eltraify, and mathematician Sophie Carr. To find out more and book tickets, visit **www.rigb.org/whats-on/ada-lovelace-day-live-0**

TIME IS RUNNING OUT

Until 3 November 2023
W5, Belfast
This temporary exhibition from the Institution of Civil Engineers explores the future of infrastructure and how civil engineers can find sustainable solutions in sectors such as transport, energy and water. Visitors can watch films and read profiles of civil engineers to discover what they do, as well as learning about award-winning sustainable engineering projects across the UK.

FLYING SCOTSMAN CENTENARY FESTIVAL

16 December 2023 to 2 January 2024
Locomotion, Shildon, Durham
At this celebration of the world's most famous locomotive, you can get involved with hands-on activities, drop-in workshops and immersive experiences, as well as solve puzzles, take part in building a gigantic sand sculpture, and get on board the story train. To find out more about the festival and other celebrations to mark the Centenary across Locomotion and the National Railways Museum in York, **visit www.railwaymuseum.org.uk/flying-scotsman/centenary-programme**

HOW I GOT HERE

HOW I GOT HERE

Q&A

NYASHA MUTEMBWA
CIVIL ENGINEER

A summer school in Shanghai inspired civil engineering student Nyasha Mutembwa to reach for every opportunity she could. She is now President of the Dundee University Students' Association.

WHY DID YOU BECOME INTERESTED IN SCIENCE AND ENGINEERING?

I was always really good at maths and enjoyed the sciences too. I enjoyed exploring why stuff is the way it is and learning how to apply it to the real world.

Initially, I wanted to do architecture. But taking part in a STEM outreach day at Brunel University when I was 14 or 15 sparked something in me to look into engineering. I eventually opted for a civil engineering degree – I knew it was what I needed to build the career I wanted (pun intended!).

HOW DID YOU GET TO WHERE YOU ARE NOW?

I set my vision, worked hard, and played hard too. I took A-level maths, chemistry, biology, and economics and got accepted by the University of Dundee.

At university, I became very passionate about engineering. I wanted to find cool opportunities that would help me grow. So, in my first year, I hesitantly applied for an incredible opportunity – a scholarship for a two-month summer school in Shanghai. I was inspired to apply after joining Dundee's Women in STEM Society, which was founded by a group of inspirational women who encouraged me to grab any experience offered to me. Fortunately, I was selected!

Nyasha helping out at the Girls in Engineering Project in Science and Engineering School with other Women in STEM members (not pictured) © Nyasha Mutembwa

It was a pivotal moment. After that, I started applying for anything I saw that excited me (and ignored the fact I might not have the experience needed or the confidence to be so out of my comfort zone).

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

I think it's been the change in my mindset and the empowerment I get from it since going to Shanghai.

Afterwards, in 2019, I was selected to attend the Future Female Engineering Conference. I also joined an all-woman Constructionarium to build a wind turbine on a construction site, where I found my passion for being a project manager. At that point, I was often travelling to London to network with other women in engineering. These experiences were key, as I was one of two Black women in all undergraduate engineering courses at the school, and that felt quite lonely at times.

(Left to right) The University of Dundee's principal with Nyasha in her role as the Dundee University Students' Association President, Honorary Graduate Dr Ollie Folayan MBE, and Dame Jocelyn Burnell © Nyasha Mutembwa

Since then, I've been shortlisted twice for Engineering Student of the Year 2022 and 2023. Also, as of July 2022, I am not only the first Black woman, but also the first engineer to be elected President of Dundee University Students' Association.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

My favourite thing is that I could transform the world if I put my mind to it. In this world there are plenty of problems still to be solved. That challenge excites me. I love thinking outside the box: diversity of thought is so important in our industry and needs to be championed!

Ever since I was a child, I've known my one priority in whatever I do is to help people and I can't imagine a better way to do that.

WHAT DOES A TYPICAL DAY INVOLVE FOR YOU?

Although I've graduated, I don't think I've ever had a typical day!

During my final year at Dundee, a day could have involved working on my dissertation, meeting with the principal about the student experience on campus (as President), or visiting local high schools (as a STEM ambassador). I also played for Dundee's women's basketball first team.

Now, I love being able to use what I've learned from my degree in my current professional role, especially the project management aspects of it.

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

Recently, someone said to me, "If not you, then who?". Despite who you see in the industry, you have every right to be in engineering. And if you enjoy it, stick to it! Your difference is what makes you unique and brings a whole diversity of thought that no one else has. It's what makes you so important to the engineering community.

QUICK-FIRE FACTS

Age: **24**

Qualifications: **BEng (Hons) civil engineering**

Biggest engineering inspiration: **my dearest friends Yewande Akinola MBE HonFREng and Dr Ollie Folayan MBE, for how they shifted my definition of success**

Most-used technology: **Definitely the phone and laptop combo. I do everything on those two but should probably decrease my screen time…**

Three words that describe you: **Black girl magic**

WHAT'S NEXT FOR YOU?

Especially since graduating, I love to say that the job for me doesn't exist yet, but it's waiting for me.

Since my honours project, I'm really interested in becoming a sustainable engineering specialist. My project was about designing sustainable, energy self-sufficient modular houses in Zimbabwe. It's such an interesting area to me, especially the link to my home country.

I'm also passionate about entrepreneurship, project management, and developing as a leader. Ultimately, I know that I am meant for big things and how I get there will be an amazing journey.

OPINION

SECURING THE INTERNET OF EVERYTHING

Internet of Things (IoT) technologies are becoming more and more embedded into our lives and societal infrastructure. Oktay Cetinkaya and Peter Novitzky, from the PETRAS National Centre of Excellence for IoT Systems Cybersecurity, argue that engineers will be key to protecting our privacy and security.

When you think about the Internet of Things (IoT), fitness trackers or smart thermostats might be among the first things that come to mind. They're designed to seamlessly connect and make our lives more convenient and efficient.

But IoT technology isn't just useful on a personal level. The 'Things' in question could be anything. Dams, dishwashers, aircraft, and Alexa speakers all count – as long as they are embedded with sensing, computing, and communication hardware; and linked to software that enables them to collect and send data, and automatically perform actions. For engineers, this means unprecedented access to measurements of the systems, devices, vehicles, and structures they design and build.

MORE DEVICES EQUALS MORE CYBERATTACKS

Statista estimates that there are already about 17 billion IoT devices in the world. Some analysts believe there could be 42 billion IoT devices by 2025. With this explosion in their numbers, plus the many different types of application that now exist, security and privacy have become a pressing issue.

Indeed, cyber incidents involving IoT devices are constantly on the rise, highlighting the urgency with which we need to address security vulnerabilities and protect user data. For example, while a Peloton fitness bike might seem harmless enough, in 2021, cybersecurity experts claimed they had found a way that hackers could gain access to monitor users via its camera and steal sensitive data. Clearly, this issue demands our attention.

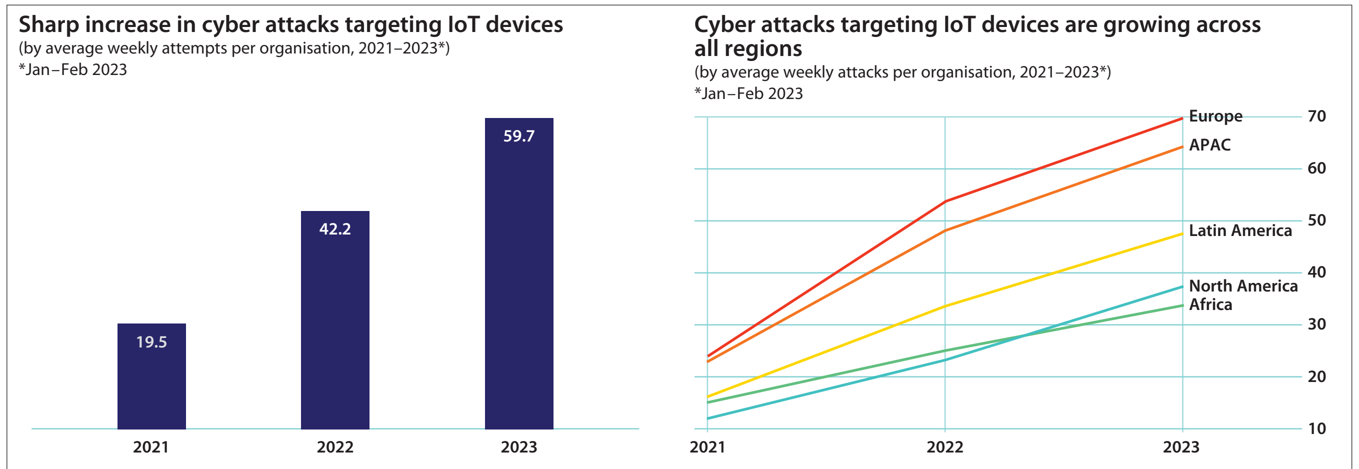
Engineers play a crucial role in designing smart and sustainable systems, making our critical infrastructure – transportation systems, communication networks, and power grids – ever more capable and efficient. IoT is at the heart of this evolution.

For example, IoT devices could help track the complete journey of energy until it arrives in our homes, from its generation to distribution. A smart grid enabled by IoT could help to balance supply and demand to avoid disruption as well as overproduction of energy. At the same time, it could also inform other linked infrastructure, such as water systems. For example, when demand on the grid is high, tasks such as pumping water into reservoirs could be automatically deferred, as it doesn't have to run at a specific time.

However, as with personal devices, networking our interconnected critical systems and processes brings heightened cybersecurity threats, which we must address now. For example, cyberattacks are a growing concern for energy companies, and IoT sensors networked into the grid could provide attackers with another way in if not secured effectively.

PRIVACY, ETHICS, TRUST, AND SECURITY

The greater convenience afforded by IoT also comes at the price of increased data collection and sharing. Such a practice may infringe upon our privacy, personal safety, or access to services. For example, if vehicle data is shared with insurers, their assessments may account for an increased risk and thus a higher price for car insurance. Moreover, many users of domestic IoT do not realise their devices are sending patterns of information that can say a lot about their lives, and their data are



According to Check Point Research, cyberattacks targeting IoT devices are becoming more prevalent

brokered at marketplaces to marketing companies worldwide.

IoT devices are already in many of our homes, workplaces, and public spaces. As their numbers and our uses for them grow, it will become more and more difficult to opt out of data collection in situations when we may not want to be monitored.

To address these issues, researchers are focusing their efforts on developing so-called privacy-enhancing technologies (PET). These aim to maximise the benefits made possible by data collection, while reducing potential harms. One well-known example of a PET is onion routing – a way of anonymising user data online.

It is not only privacy (individual control over data shared) that is important here. Even voluntarily sharing too much information can make people vulnerable and organisations unsafe. For example, sensitive inferences can be drawn from combinations of apparently unconnected devices that collect seemingly innocuous metadata (for instance, the time and date data is created).

Hence, data must be collected and processed responsibly. Cybersecurity measures must be robust and follow international principles and national regulations for ethical and legal conduct. Importantly, compliance should be monitored to preserve human rights and personal dignity.

RESPONSIBLE DIGITAL CITIZENS

We are constantly reminded that new and emerging technologies, with all their promise, can have unforeseen consequences. For example, social networks, generative AI, and smartphones have all played a role in the contagious spread of misinformation.

As a new technology, IoT could be dangerous if it enables harm to critical infrastructure such as our water services, healthcare or political systems, or individual wellbeing – from sleep to mental health. IoT has already caused concern through its role in facilitating domestic violence, through eavesdropping with smart speakers and stalking with IoT tracking devices, for example. It's critical that experts worldwide work in partnership with users to develop tools that enhance digital literacy and 'cyberhygiene'; and teach the next generation how to use technologies safely and smartly.

PROTECTING OUR DIGITAL WORLD

The ever-growing world of interconnected IoT devices will require many different talents and types of innovative thinker to solve the technical, social, cyber, and physical challenges that lie ahead.

Engineers will be at the heart of addressing these challenges and must be ready to work with colleagues across disciplines, including design and behavioural sciences as well as computing, communications and software.

For example, more robust cybersecurity standards will require encryption experts, but also social scientists and user-centric designers. The latter can investigate how humans can interact safely – or indeed, unsafely – with devices. Collaborative efforts from researchers in universities and industry across many disciplines will be essential to creating a safe and trusted IoT environment that benefits people.

Engineers at all career stages are invited to join this grand challenge to release the transformative power of IoT. Your contributions can make a significant impact, either by staying informed, promoting awareness, or advancing the science and engineering associated with IoT. Together, we can help build a more secure and connected future.

With thanks to Gideon Ogunniye, Joe Bourne, Jeremy D McK Watson CBE FREng, Rachel Cooper OBE, Julie A McCann, David De Roure, Tim Watson

ABOUT PETRAS

The PETRAS National Centre of Excellence for IoT Systems Cybersecurity – a seven-year, EPSRC-funded partnership of 24 universities – connects many researchers across social and physical science disciplines with industry and government to tackle these issues in theoretical, practical, and impactful ways. Jeremy D McK Watson CBE FREng is the centre's the Director and Principal Investigator.

UNDERSEA INFORMATION SHARING

UNDERSEA INFORMATION SHARING

Illustration for *Ingenia* by Benjamin Leon

Did you know?

- Undersea cables, totalling more than 1.3 million kilometres in length, carry almost all of the world's telecommunications traffic
- The fastest subsea link connects the east coast of the US to the west coast of France, delivering 250 terabits a second across the Atlantic
- Sensors on submarine cables are increasingly being used to track environmental events such as earthquakes

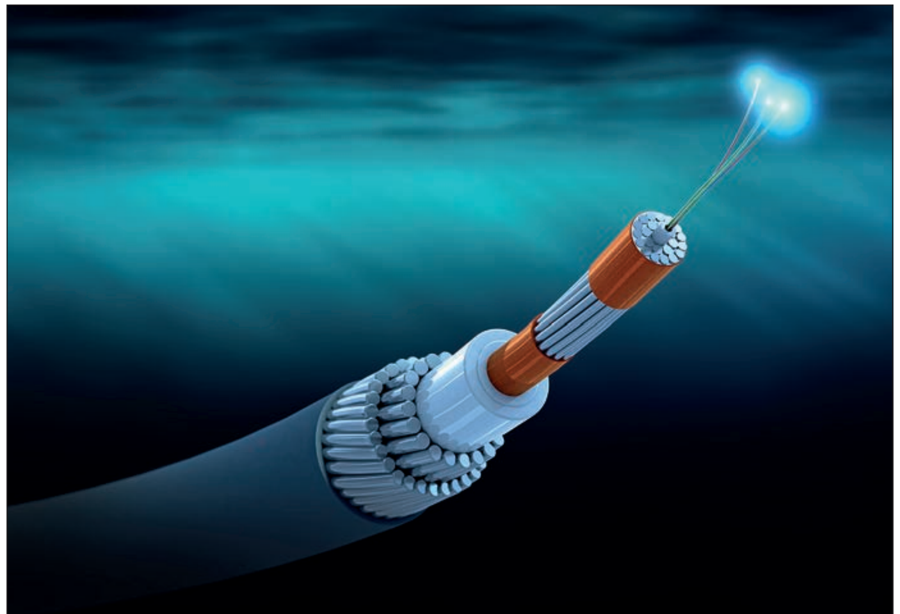
As our lives becomes more digitised and our entertainment, work and day-to-day tasks are increasingly online, network operators are laying more submarine cables with ever higher capacities to support our growing reliance on data services. Susan Curtis discovers how scientists and engineers are finding ways to boost the capacity of subsea networks – and even using them for additional purposes such as tracking migrating whales.

Our growing reliance on mobile and digital technologies is driving an almost insatiable demand for data. During the COVID-19 pandemic, people started increasingly working from home and kept in touch with colleagues, friends and family via video calling. This, coupled with widespread use of streaming services, 5G mobile networks and online gaming, saw global internet usage rise by almost 30% a year between 2017 and 2021. And these numbers show no sign of slowing down: new applications and digital services are released every year, millions more people are becoming connected to the internet, and we are living more of our lives online.

Network operators are responding to this surging demand by extending their fibre networks, providing dedicated, high-speed connections to homes and businesses to support data-hungry services such as video platforms and cloud computing. This urgent need for extra capacity and ever-faster speeds also extends to the long-distance optical cables that criss-cross the world's oceans, laid on the seabed. Between them, these subsea cables carry some 99% of the world's telecommunications traffic.

As a result, there has been an increase in installations of these cables across all major routes. Most new deployments are funded by organisations such as Google, Amazon, Microsoft, and Meta, which together account for about two-thirds of all internet traffic – and an astonishing 90% on the busiest transatlantic links. According to figures from industry analyst TeleGeography, over $10 billion worth of new subsea cables will enter service between 2022 and 2024, and demand on these links is expected to increase at a compound annual rate of 30% to 50% between 2021 and 2028.

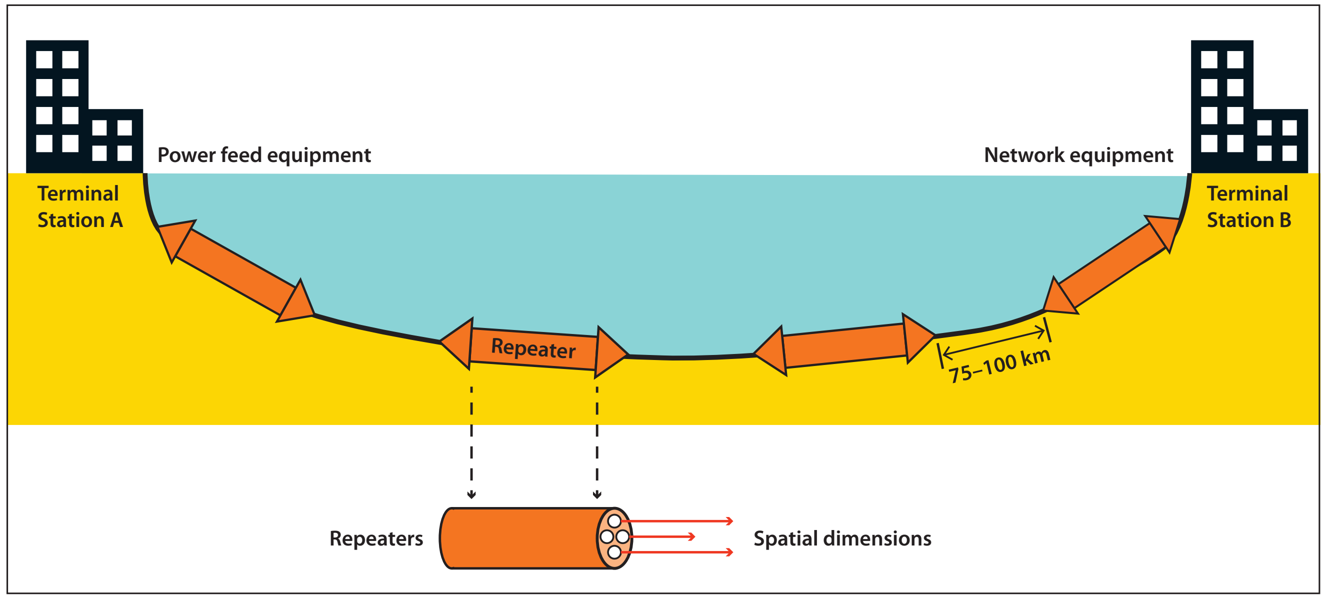
Each new deployment costs hundreds of millions of pounds, so



A submarine cable must be engineered to survive the underwater environment for several decades, while also providing sufficient power to maximise the amount of data that can be sent through each fibre pair. A layer of copper is used for its electrical conductivity, while steel cladding strengthens the structure

UNDERSEA INFORMATION SHARING

CABLE SYSTEM



A submarine optical cable provides a communications link between two or more landing points. At each end of the cable, a landing station houses the optical transmission equipment that sends and receives the optical signals, along with a power-feeding system that supplies a continuous direct current to a series of optical repeaters installed along the length the cable. In conventional systems the repeaters contain a dedicated optical amplifier for each fibre, but the number of fibres that can be supported is then limited by the amount of power that can be delivered from the landing stations. In contrast, an SDM system shares the available power between the optical channels, making it possible to increase the number of fibres and boost the data-carrying capacity of the cable.

engineers need to design submarine cable systems with longevity in mind. Intense technical innovation has focused on increasing the capacity to send more information over each subsea link, with many cables now carrying more than one hundred terabits per second (Tbit/s). The current record is held by Google Cloud's Dunant cable, which supports 250 Tbit/s – equivalent to sending the full digitised collection of the world's largest library, the US Library of Congress, three times every second – over a 6,600-kilometre link connecting Virginia Beach in the US with Saint-Hilaire-de-Riez in France.

HUNGRY FOR DATA

Such capacity increases have generally been the result of ongoing advances in the optical and electronic equipment installed at each end of the submarine cable, which have boosted the amount of data that can be sent through each optical fibre within the cable. In particular, the introduction of so-called coherent transmission technologies has made it possible to send and receive the complete optical signal rather than just the intensity of the beam, delivering a 10-fold increase in capacity since 2010.

However, packing more data into individual optical channels also means that each one needs a greater power supply. For subsea links, that power can only be delivered at the landing stations at either end of the cable, with periodic repeaters installed along its length to maintain the signal strength over intercontinental distances.

This challenge places a practical limit on the number of fibres that can be supported within a subsea link, with even the most advanced systems only able to carry data over 16 optical fibres. In telecoms networks these individual fibres are traditionally formed into pairs, with each fibre pair carrying two-way communications traffic. "The capacity we can achieve is limited by the power of the subsea cable," explains Jeremie Renaudier, a lead researcher at Nokia Bell Labs in France. "We cannot increase the number of fibre pairs in these systems without having enough power to optimise the capacity and performance of each one."

Creation of the Dunant cable marked a change in strategy. A complete redesign of the system architecture meant that the fibre pairs could share the available power, rather than each one having its own dedicated power source. This power-sharing scheme, called space-division multiplexing (SDM), enabled Dunant to become the first long-distance subsea cable to support 12 fibre pairs – rather than eight – delivering a 40% increase in capacity. "The system is suboptimal on a per-fibre basis, but distributing the power increases the capacity of the whole cable," explains Renaudier.

The success of the approach means that submarine links supporting 16 optical channels are already coming into operation, while two long-distance SDM systems capable of transmitting about 500 Tbits/s over 24 fibre pairs will soon enter service: the 2,600-kilometre Confluence-1 system that will connect Miami with New York in 2023, and the EU-supported 8,800-kilometre Medusa cable that is due to link Europe with North Africa in 2024.

A TIGHT SQUEEZE

However, the demanding subsea environment places other practical limits on the number of fibre pairs that even an SDM system can support. At the most fundamental level, all of the fibre pairs must fit into a standard-sized cable, which is typically 17 or 24 millimetres across. "These cables are made from expensive materials, and so increasing the cable diameter adds significantly more cost into the system," explains Fatih Yaman, a senior researcher at NEC Labs in the US.

As a result, current research is focused on squeezing more fibre pairs inside a standard-sized cable, with the limit expected to be about 32 or possibly even 48. At the same time, cable companies such as NEC are already preparing for a future when it will no longer be economically viable to add more fibres into the cable, and Yaman believes that the most obvious way forward is to introduce more sophisticated fibre technologies that support multiple optical cores. "Multicore fibre (MCF) is the only way to scale the number of optical channels without increasing the cable diameter," he says.

Indeed, NEC engineers have been working with fibre manufacturer Sumitomo Electric to develop a prototype submarine cable based on four-core fibre, with each one supporting 16 fibre pairs. In laboratory tests simulating real-world conditions, a 3,000-kilometre cable delivered a capacity of more than 1.7 petabits per second, and in 2021 the company completed the first field trials of its prototype design.

While MCF could become technically feasible, it is currently much more expensive to produce than standard fibre. "It's not yet clear whether it's a technical limitation or mainly a question of manufacturing volume," says Yaman. "The issue for the industry right now is how fast and how far the costs come down as volumes increase."

UNDERSEA SENSORS

While the telecoms industry is focusing on maximising the capacity of these networks, environmental engineers are hoping to unlock the optical information transmitted by underwater links to create a global network of geophysical sensors. Any underwater disturbance can affect an optical signal as it travels along a fibre, which scientists have already exploited to detect the vibrations caused by seismic and storm activity. Researchers in Norway have even shown that a submarine cable can pick up the sound of singing whales, offering an effective way to track their migration along the Norwegian coast.

Several different sensing modalities have been developed and tested in recent years. The Norwegian whale trackers used a technique called distributed acoustic sensing (DAS), which listens for underwater sounds by sending an optical pulse through a fibre and then analysing the signal that is reflected back from different points along the cable. While this technique can pinpoint the source of the sound to within a few metres, its range is limited to a few hundred kilometres from the shoreline.

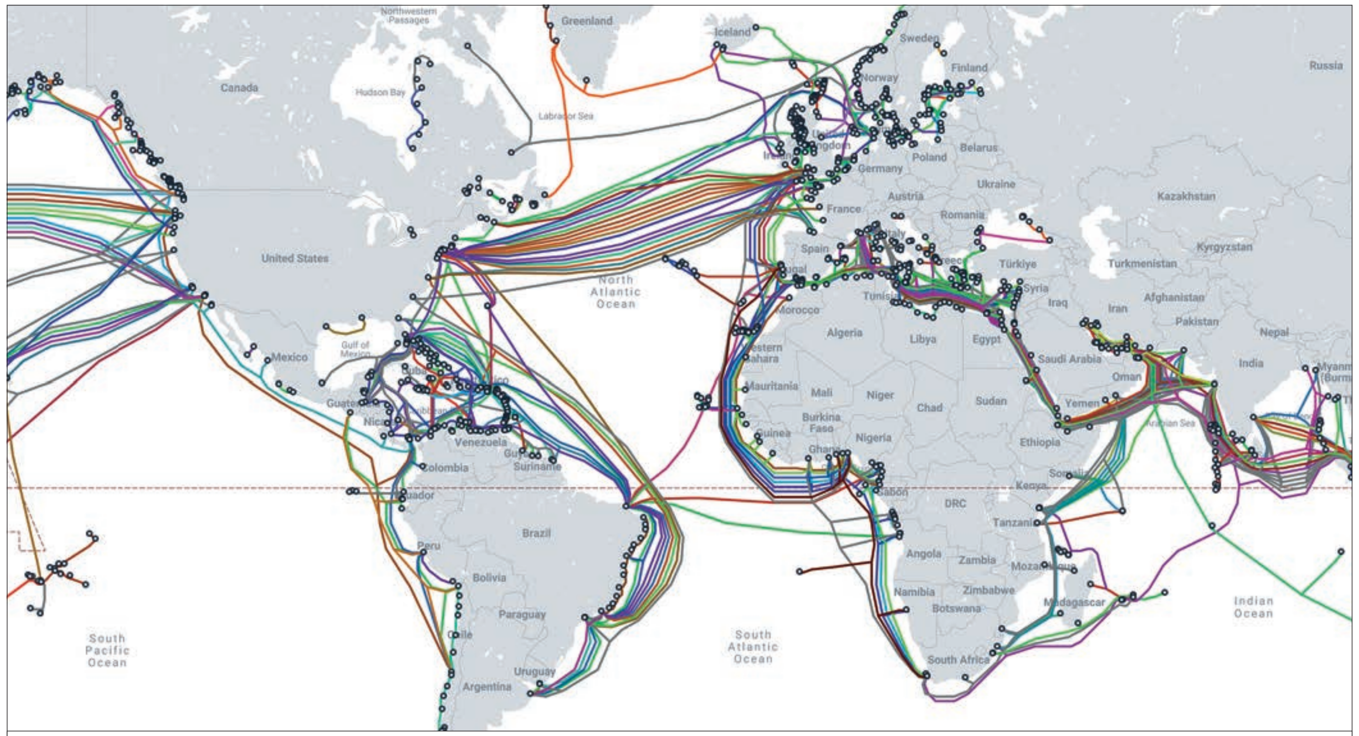
Other approaches unpack the information in an optical signal after it has travelled through the length of the cable – making it possible to detect vibrations and acoustic disturbances over much longer distances. In 2018 a team led by Giuseppe Marra, Principal Scientist in the National Physical Laboratory's (NPL) time and frequency department, demonstrated a technique for detecting earthquakes using standard communications cables. By sending light from an ultrastable laser through a terrestrial link a few hundred kilometres long, the team could measure changes in the optical signal that were caused by seismic events up to 18,500 kilometres away.

Then, in 2021, a collaboration between the California Institute of Technology and Google showed that regular telecommunications traffic could detect earthquakes as well as storm-driven ocean swells. Using data collected over a 10,000-kilometre submarine cable, the team recorded about 30 storm-swell events and multiple moderate-to-large earthquakes over a period of nine months, including the magnitude 7.4 earthquake event that happened near Oaxaca, Mexico, in June 2020.

While promising, the downside of these techniques is that they measure the cumulative effect on the optical signal over the entire length of the cable. That makes it difficult to locate the source of the disturbance, such as the epicentre of an earthquake, without further information from other cables or monitoring systems. Noise also builds up along the length of the fibre, preventing the detection of smaller environmental events.

In 2022 the NPL team addressed this issue by adapting its technique to measure the change in optical signal between the repeaters on a 6,000 kilometre section of a cable, rather than over the whole length. "With our previous work the cable acted as a single sensor," explains Marra. "In this new study we have exploited the technology inside the optical repeaters to transform the cable into an array of sensors, where each sensor is now the span between each repeater."

The team tested its updated scheme over several months using a live communications link between the UK and Canada. As well as detecting earthquakes, the team could locate the source of individual events and track their evolution in both space and time. The measurements also revealed the effects of ocean currents, as well as periodic disturbances that the team



The world's oceans are home to more than 1.3 million kilometres of optical fibre providing critical communications links all over the world © TeleGeography

attributes to tidal activity. "An integrated view over the whole cable picks up lots of events, but it's difficult to make sense of them," comments Marra. "With this technique we can pick out features in specific sections of the cable, which makes it a much more powerful tool."

Marra is confident that the team's experimental set-up could easily be engineered for use with other submarine cables, since no changes are needed to the existing underwater infrastructure. "Currently there are very few permanent sensors on the ocean floor," he says. "Scaling the technique would provide thousands of underwater sensors all over the world, which could be revolutionary for seismology and for our understanding of ocean circulation and the impacts of climate change."

SMART CABLES

Longer term, environmental engineers are calling for future subsea cables to be fitted with dedicated sensors to measure pressure, temperature and acceleration. This will provide a more comprehensive monitoring system for early detection of seismic events, as well as for climate and ocean observation. The sensing technologies needed for such Science Monitoring And Reliable Telecommunications (SMART) cables have already been demonstrated in underwater geophysical observatories, notably two large-scale networks in Japan that were deployed in the wake of the 2011 Tōhoku earthquake and tsunami. However, more work is needed to demonstrate a practical SMART cable that meets the needs of commercial telecoms operators as well as environmental scientists.

Several pilot projects are now hoping to prove the technology's feasibility, generally in areas most at risk from seismic events and climate change. As an example, SMART functions are being integrated into a planned communications link between the Pacific islands of New Caledonia and Vanuatu – in the heart of the 'Ring of Fire', a horseshoe-shaped string of volcanoes and seismic activity in the Pacific basin – and the five-year programme recently received a $7 million funding boost from the Gordon and Betty Moore Foundation.

Even more ambitious is the CAM-2 project, which in 2025 is due to replace an existing cable that links Portugal with the Atlantic islands of Madeira and the Azores. SMART sensors will be embedded in about 50 repeaters along the 3,700-kilometre route, accounting for about 10% of the €12 million budget. Three tectonic plates converge in the region, so the government-backed project aims to provide early warnings of earthquakes and tsunamis for the Portuguese mainland.

While SMART cables might remain limited to smaller projects for the foreseeable future, Marra hopes that the data they provide might be able to validate and refine the results provided by all-optical methods operating across longer subsea links. "The availability of SMART cables would really help us to improve our technique," he says. "Combining the rich data from small-scale SMART systems with the reach we can achieve with the existing underwater infrastructure would really benefit the scientific community."

This article has been adapted from an original, Subsea Fiber: Into the deep, published by Optics & Photonics News *in March 2023: www.optica-opn.org/link/0323-subsea. With thanks to the editor and publisher.*

The 1915Çanakkale Bridge during construction of the central deck section © Shutterstock

BRIDGING THE EURASIAN GAP

The world's longest suspension bridge opened in Turkey last year. It opened a year ahead of schedule, largely because of the contribution of a small UK engineering company. DLT Engineering designed and supplied the award-winning deck lifting gantries that shaved months off the construction time. Hugh Ferguson talked to Mercedes Ascaso Til, DLT's Principal Engineer.

Constructing a huge bridge across a busy international shipping channel presents a host of challenges. How do you minimise disruption to sea traffic? How do you keep workers safe in hazardous conditions – at height, over water, and in often ferocious weather?

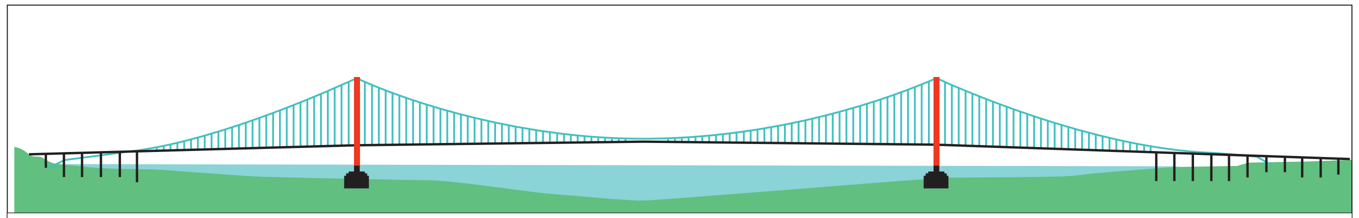
But for the 1915Çanakkale Bridge, crossing the Dardanelles Strait in Turkey, one of the greatest challenges was time, for both political and commercial reasons.

The 1915Çanakkale Bridge joins the Asian and European parts of Turkey. It is named to celebrate an Ottoman victory against an Allied naval fleet during the First World War, which took place on 18 March 1915. The contract for the bridge was signed on 18 March 2017, with its expected completion during centenary celebrations for the formation of the Turkish Republic in 2023.

The contract was let to DLSY, a Turkish/South Korean joint venture, on a 'build-operate-transfer' basis. This meant DLSY financed construction, which would then be repaid from tolls until 2033. After this point, some 16 years from signing the contract, the

Did you know?

- Ships travelling from Black Sea ports must go through two Turkish straits, including the Dardanelles, to reach southern Europe and northern Africa
- Passengers used to rely on a one-hour ferry to cross, with long waits often dragging travel times out to up to five hours
- Now it takes just six minutes to drive over the bridge



On a suspension bridge, the deck hangs from vertical cables, each of which are attached to long suspension cables spanning the bridge's length. The suspension cables hang from tall towers built in the channel, with large cable anchorages securing them to the ground at either end

toll fees would be paid to the Turkish government.

The construction works were valued at $1.68 billion. Based on the total in toll fees from the 60,000 vehicles expected to use the crossing each day, revenue of $900,000 a day was expected. So, each day saved would produce nearly $1 million extra for the contractor – a huge incentive to finish early and, vice versa, to avoid delayed completion. In the end, President Erdoğan of Turkey opened the bridge a year early on 18 March 2022.

HOW TO BUILD A SUSPENSION BRIDGE

The construction programme on suspension bridges starts with the main towers, their foundations and the cable anchorages. Next comes the two main cables, and then the deck.

For the Çanakkale Bridge, each cable was an almost metre-wide bundle of 144 steel strands (each made up of 127 wires), anchored to the land either side and supported on the two towers. As with many other suspension bridges, constructing the deck involved floating prefabricated deck sections to site by barge, hoisting them into position, connecting them to hangers from the main cables, and then welding deck sections together.

But where the Çanakkale Bridge differed from most suspension bridges was by its innovative approach to assembling the deck, which saved months of construction time. Key to this was a piece of equipment called a gantry, which would do the heavy lifting once manoeuvred into place; and a sophisticated control system to coordinate its movement. Thanks to this system, two of these specially designed gantries could hoist two deck sections in tandem – up to 48 metres long altogether – to their final positions.

UK-based DLT Engineering designed and supplied these cutting-edge gantries, each of which weighed in at 260 tonnes – about twice the weight of the average blue whale. They worked with DLSY and Çanakkale's Danish bridge designer COWI, having trialled a prototype version of the same design with great success on the Nizhou suspension bridge in southern China. Twelve engineers and technicians from DLT's Darlington office worked on the project, led by Principal Engineer Mercedes Ascaso Til, with support from DLT's other offices.

Similar to how a butterfly spends far longer in a cocoon than as a butterfly, the gantries spent about two and a half years in design, manufacture and testing. It then took engineers just two months and one day to build almost 3.4 kilometres of deck. Ordinarily, this would take many months.

A CABLE-CRAWLING, SELF-ASSEMBLING GANTRY

According to Mercedes, who managed most of the process remotely from Darlington, the greatest innovation was the self-erecting, self-dismantling gantries – a world first.

Normally, to build the central span between the two towers, barges transport gantries to the midpoint of the bridge. A floating crane then lifts the gantry to the lowest point of the cables, temporarily blocking the middle of the channel.

The problem is, floating cranes large enough to access the cables more than 100 metres above sea level are expensive to hire, and companies have to book them months in advance – leaving no flexibility in the programme. Miss the slot and another may take ages to arrange; save time in

The gantry during construction, pictured from the centre of the bridge © DLT Engineering

the run-up, and the savings are wasted waiting for the crane.

Alternatively, gantries can be assembled using cranes on the towers. However, this method can add several days onto the process. Not only does it require temporary frames to be constructed on the towers, but the gantries must be lowered along the cables to where they will start lifting deck segments.

But what if the team could transport the gantries by barge, attach them to the bridge's main cables, and lift them with their own jacks? And what if it could be lifted at any point in the span? This would remove the need for floating cranes, while also minimising disruption of sea traffic in the centre of the channel.

Mercedes' and DLT's ingenious self-erecting system made this possible. This delivered the gantry in three sections to the main cable level, via a steel lifting frame with strand jacks attached at either end, 38 metres apart – the same as the two main cables. This auxiliary structure supported the gantry until it was assembled into its final configuration and lowered onto the main cables (see box 'Assembling the gantry').

The tricky part was to ensure the three 3D gantry sections were safely connected – not easy on a deflecting, moving structure, 100 metres above water. To ensure this would be exactly right, the DLT team took months ("if not more than a year") to analyse the structure, devise the scheme, and even do a trial run of the self-erect.

In this setup, DLT used a device called a strand jack to move the gantry up and along the cables. This comprised a hollow hydraulic cylinder with a set of steel cables (called 'strands') passing through clamps at either end of the cylinder. It operates similarly to a caterpillar's walk, climbing along the strands by releasing the clamp at one end, expanding the cylinder, clamping again, releasing the trailing end, contracting, and clamping the trailing end before repeating. While slower than cranes or winches, strand jacks can move very heavy loads safely and with great precision, and were also used to lift the deck segments.

DLT used a computer control system designed in-house, which enabled a single operator to control each movement. The computer synchronised movement of all of the jacks within millimetres, and loads on each jack were continuously monitored and adjusted accordingly. This was critical as the forces could vary substantially as the bridge moved under loading or wind forces.

All the gantry equipment could be controlled by a single operator with a single centralised computer system, although up to five people were needed per gantry during key operations such as moving the gantry along the main cables.

LIFTING THE DECK

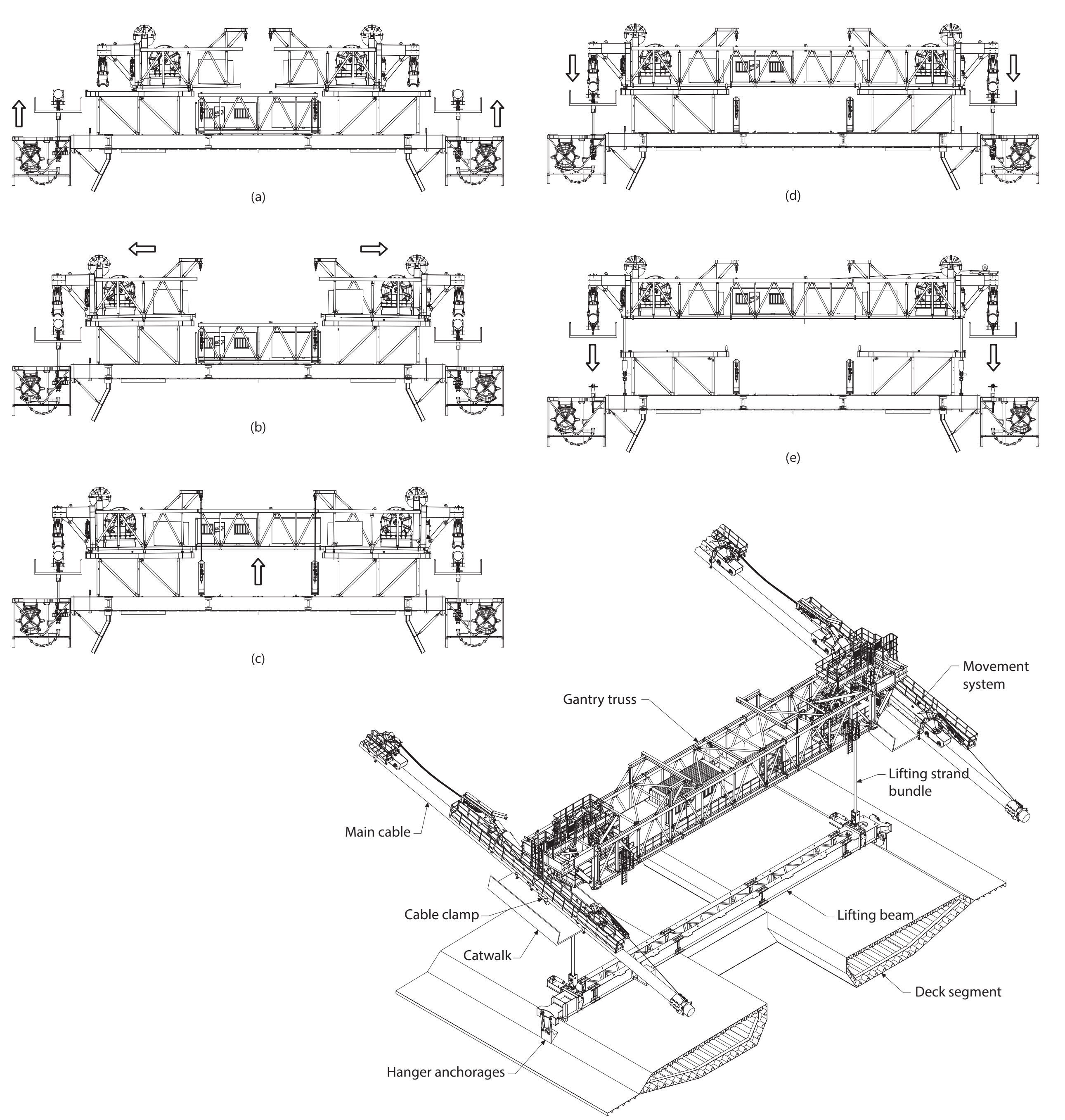
Once in place, the gantries had to be moved along the main cables to the right position on the cables for each lift. The strand jacks were used for this, too.

When stationary, or during lifting, the gantry rests on steel supports clamped to the main cables. For movement along the cable, its weight is transferred onto a set of nylon wheels running on the cables. The challenge here was that the cable clamps, which connect to the hangers that support the bridge deck, protruded above the cable. DLT's innovation was to introduce small aluminium wedges that acted as ramps, allowing the nylon wheels to ride up and over the cable clamps. Each wedge had to be articulated and carefully contoured to transfer the weight smoothly.

Tandem lifting was another unique innovation. Each section of the deck was typically 24 metres long to match the spacing of the hangers and weighed up to 420 tonnes. Assembling deck sections in pairs on land beforehand, and then lifting them with two gantries, produced a considerable time saving. It also halved the number of interruptions to the shipping channel.

"I was delighted to see how easy and fast it was to move the gantries along the main cables," says Mercedes, who visited the site to provide technical support for an especially complex 'block lift' near the towers, involving four gantries and three deck sections. She adds that according to the main contractor of the Nizhou Bridge, the time taken to relocate the gantry for each lift was reduced by about two-thirds, compared to traditional methods.

ASSEMBLING THE GANTRY



(Above) The sequence of DLT's innovative self-erection system for the gantries. The gantry is installed in three parts on the lifting frame, barged to site and lifted up to the main cables (a); the two outer parts were now above the main cable, and could be winched out to enable the central section to be lifted and connected (b) and (c); the weight could then be transferred to the main cables via the gantry's movement system (d) and the lifting frame lowered back down to the barge (e). (Below) Once assembled, the gantry was able to lift sections of deck into place

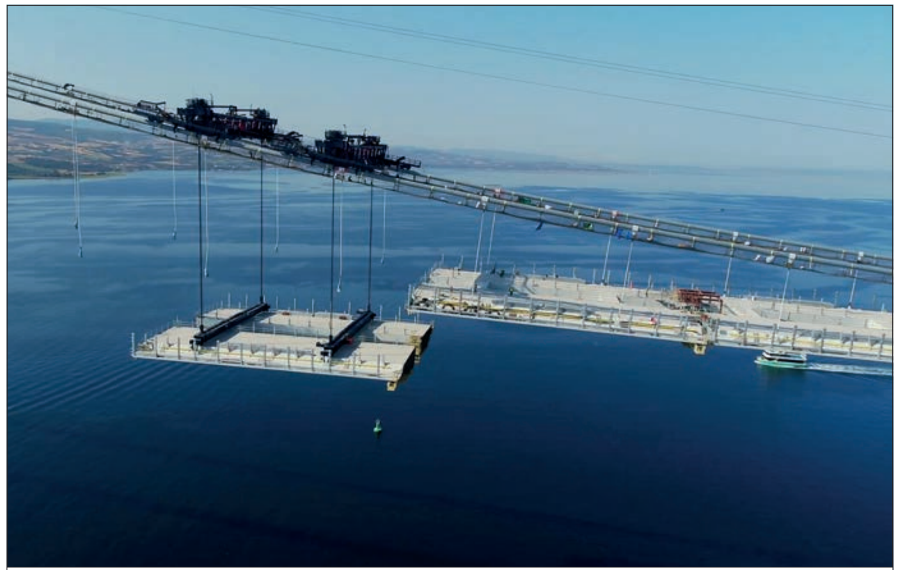
To maximise speed, DLSY used eight gantries, four for the main span and two each for the side spans.

Placing each tandem deck took about 10 hours. In parallel, across the eight gantries, the team managed to execute up to four tandem lifts a day. In ideal conditions, DLT could have built all the standard deck units in less than four weeks. In reality, it took two months, because only two barges were available to deliver the units, and because of adverse weather. The gantries could operate in wind speeds of up to 20 metres per second, equivalent to a so-called 'strong breeze'. "I can assure you, that feels very strong on the bridge catwalk, and not safe for workers to be operating there," says Mercedes. However, conditions were frequently worse.

The sections of deck immediately beneath the towers presented an extra challenge, solved with a unique 'block lift', involving four lifting gantries, two either side of the tower. Here, the team was working with a 1,200-tonne block made up of three sections of deck. At this stage, the part-complete main span deck was continuously moving in the wind, so the team had to carefully synchronise the strand jacks, and only perform these lifts during periods with wind speeds slower than 10 metres per second.

DLT ENGINEERING

DLT Engineering was founded in 2000 but can trace its links to historical companies formed in the 19th century. As such, the company has a long and distinguished history in the construction of landmark structures around the world, particularly iconic bridge works and building structures such as the Queensferry Crossing or the Wembley Stadium. Today, DLT Engineering is a private company, Chinese-owned but still with an engineering office in Darlington and head office in Higham Ferrers, England.



A close up of the tandem lift © 1915Çanakkale and Motorway Project

"I was thrilled to see the bridge across the strait and our gantries in operation. They moved so smoothly," says Mercedes. "I took so many videos and photos. It was one of the best moments of my career."

DISMANTLING THE GANTRIES

With their work complete, the gantries self-dismantled. This involved a modified reversal of the self-erection sequence, where they were lowered to deck level near the towers and broken down. Then, the pieces were lowered through the gaps in the deck between carriageways onto barges for removal.

DLT won an innovation award for the Çanakkale gantries at last year's British Construction Industry Awards. Earlier in 2023, the prototype Nizhou gantries were used to complete the deck of the ShenZhong suspension bridge, part of a 24-kilometre long crossing of China's Pearl River now under construction. DLT Engineering is now hoping for a commission for its gantries on the forthcoming ShiZiYang suspension bridge, also on the Pearl River estuary.

This will create a new world-record span of 2,180 metres and will also be much heavier than Çanakkale, with twin decks each carrying eight lanes of traffic, and main cables more than 1.4 metres in diameter. However, this may yet be overtaken by the ZhangJinGao Yangtse River Bridge, where construction of tower foundations is already underway, with a 2,300-metre main span.

Long-span suspension bridges are getting longer.

BIOGRAPHY

Mercedes Ascaso Til is Principal Engineer at DLT Engineering Ltd, with over 20 years of experience in bridge engineering. In 2019, she received *New Civil Engineer*'s Technical Excellence Award. In 2022, the Women's Engineering Society selected her as one of the Top 50 Women in Engineering: Inventors and Innovators. In addition, the gantries won the Innovation Product of Year Award at the British Construction Industry Awards 2022 and were shortlisted for the IStructE Awards 2022. Mercedes is passionate about music, theatre, philosophy, poetry, travelling, art, and much more.

Hugh Ferguson would like to thank Mercedes Ascaso Til, Principal Engineer with DLT Engineering; Tina Vedrum, Senior Technical Director Transportation International at COWI and President of the International Association for Bridge and Structural Engineering (IABSE); and Richard Hornby, Long Span Bridge Lead at Arup who conducted independent design verification for the bridge, for their help in producing this article.

PROTECTING THE UK'S COASTS

Erosion at Birling Gap, in Sussex. Several houses have been demolished, instead of being allowed to collapse over the cliff edge
© pxl.store / Shutterstock

PROTECTING THE UK'S COASTS

Coastal erosion is an urgent problem in the UK and around the world. Leonie Mercedes explores how engineers are constantly working to manage coasts and protect communities with an arsenal of tools, such as sandscaping and numerical modelling.

About 28% of English and Welsh coastline is vulnerable to erosion, with 6% losing more than a metre of land each year. Communities across the country are under threat, but the east of England is particularly vulnerable because of the largely softer sediments making up the coastline. Norfolk villages Happisburgh and Hemsby, which face out to the North Sea, have between them lost over 50 homes to erosion during a 20 year period, forcing residents to relocate.

Climate change is only making matters worse, with rising sea levels and stronger storm activity speeding up rates of erosion. According to research by climate action group One Home, if no action is taken, 21 villages and hamlets will be lost to coastal erosion by 2100, representing £584 million worth of residential property. In many cases, residents are not compensated for losing their homes, and may even have to pay thousands towards the cost of demolition. So, how are engineers working to protect the country's coasts?

Did you know?

- Coastal erosion is a natural process, influenced by factors including sea-level rise because of climate change, and subsidence, or sinking land
- Subsidence can be down to human activities such as groundwater or oil and gas extraction, and natural processes, such as the Earth's continued adjustment to the last ice age
- The latter is a major factor for the UK and has caused our east coast to continually sink relative to the sea. As a result, the coastline is eroding to find an equilibrium

SOFT VERSUS HARD ENGINEERING

Approaches to reducing coastal erosion can be split into two categories: hard and soft engineering.

Hard engineering involves building structures to reduce energy transport from the ocean to the coast, such as sea walls, groynes, and rock armour. Soft engineering tends to use natural resources such as sand or vegetation, and often harnesses the forces of nature.

Interventions to coastal erosion have historically involved hard engineering. However, it's now recognised that these solutions disrupt natural coastal dynamics, and can, for instance, increase erosion further down the coast, effectively moving the problem elsewhere. With a greater understanding of the dynamics of coastal areas, we now – when possible, and appropriate – tend to opt for a softer approach.

"There's definitely a strong move to soft, and working with sediment," says Robert Nicholls, professor of climate adaptation at the University of East Anglia and director of the Tyndall Centre for Climate Change Research. "It's flexible, it can adjust to changing conditions – it has multiple benefits." However, he notes: "With any response, it's not forever. It's for a period of time."

One such technique, sand nourishment, is where large volumes of sand – traditionally hundreds of thousands of cubic metres – are deposited on strategic points on the shore to keep beaches topped up with sediment. It is also called 'sandscaping' (typically when done on a larger scale and when designed to harness the prevailing forces of nature).

Nourishments can be a more environmentally sound alternative to hard coastal defences, if they are designed to work with the forces of nature. This means that wind, waves, and currents redistribute the sand gradually, which avoids disruptive changes to beach habitats. Nourishments can adapt to rising sea levels, and do not simply move erosion further along the coast. As they are, in effect, widening the beach, they can restore or create habitats for the flora and fauna that make the coast their home. Hard defences, built to prevent cliff erosion, can exacerbate the problem they were brought in to solve. After nourishment, the new sediment replaces the sand that would have been released by the eroding cliff.

With traditional nourishments, the sand must be replaced each spring. However, new approaches to nourishment are making the intervention more efficient and long lasting.

Nicholas Dodd, professor of coastal dynamics at the University of Nottingham, is working on such approaches with his team. For instance, some involve dumping the sand further offshore in an area called the shoreface – where the seafloor slopes downward from the beach. "These big shoreface nourishments would slowly move onshore, under natural processes," says Dodd. "It's a very, very gradual process, much less dramatic than during a storm."

Shoreface nourishments were first carried out in the Netherlands in the early 1990s as a proactive rather than reactive approach to coastline protection. Compared with beach nourishments, they are longer lasting, generally cheaper, and avoid inconvenience on the beach.

WHAT CAUSES COASTAL EROSION?

Erosion is the physical removal of land by the sea. The two main mechanisms that drive erosion are wave motion, which is generated by wind; and mean currents beneath the surface of the waves, which are created by waves and tides. These waves and currents in the near-shore region move sediments from one location to another.

As sea levels rise because of climate change, the area affected by erosion will move further inland. Meanwhile, it is thought warming will result in heavier rain and more frequent flash floods. Flooding of coastal areas is connected to (and hastens) coastal erosion.

De Zandmotor beach in the Netherlands in 2016 © Zandmotor/Flickr

"The Dutch have a particular interest in protecting their coastline," says Dodd. Over 250 kilometres of the Dutch coastline is protected by sand dunes – damage to which can cause disastrous floods. So, they didn't stop at the shoreface. In 2011, Dutch engineers built De Zandmotor ('sand motor'), an artificial peninsula near the Hague.

Aiming to protect nearby dune systems for 20 years, they dumped 21.5 million cubic metres of sand along the coast. A nourishment on this scale is also called a 'sand engine' or 'mega nourishment'. (For context, the O2 in London has a total volume of 2.2 million cubic metres.)

"You've deposited so much sand that it changes the behaviour of the waves," explains Dodd. "The idea is [to] alter the direction in and intensity with which the waves and currents move the sand and therefore possibly alleviate erosion."

With the long-term protection afforded by sand engines, councils save on the cost of renourishing each year. "Over the course of time, the waves will naturally spread that enormous quantity of sand that has been deposited there along the coast," says Dodd. In the case of De Zandmotor, it's now thought it will provide protection for much longer than 20 years.

A 2021 study into the effectiveness of sand nourishments in the Netherlands over the past three decades concluded that all types of nourishments combined have successfully maintained the position of the country's 432 kilometres of coastline.

In recent years, local councils in the UK and their partners have followed suit, depositing drastically increased volumes of sand. The UK's first sand engine, placed in north Norfolk in 2019, continues to protect thousands of people living in the villages of Bacton and Walcott, as well as the Bacton Gas Terminal, which supplies a third of the UK's gas (see box 'The UK's first sand engine').

A MODEL SOLUTION

To help design their coastal defences, whether hard or soft, engineers use computer-based numerical models to simulate real shoreline processes.

Numerical modellers select appropriate equations to simulate how coastal systems behave, and then solve the equations using specific techniques. No one model can describe an entire coastal system: rather, engineers simulate processes at different time and length scales. Engineers can then conduct experiments using those models to understand how a system might evolve with or without an intervention.

For example, engineers at Imperial College London used numerical simulation to determine how a breakwater structure comprising 20-tonne concrete units would fare against stormy seas.

Numerical models help engineers design the defences that will perform the best in certain locations, and do so within budget. "Much of the work that we would do in beach nourishment is develop numerical models that improve our ability to simulate how the nourishment will behave," says Dodd. "We ideally want to know what the intervention will do."

How accurately can models reproduce real processes? "That's an ongoing area of research," says Dodd. "There's always a trade-off between the complexity of the model – the amount of physics that the model would include – and how long you could run that model for over one spatial scale," he says.

To enable these simulations, engineers must use abstracted models. This means that, for example, if you wanted to simulate cliff retreat along the English coast over the course of 1,000 years, rather than simulating the effects of individual waves, you would aggregate the effects of those waves.

Harnessing the insights produced by numerical modelling and making them easier to digest can also make decisions easier for councils. In a former role as an engineer in consultancy, Jack Heslop (now senior research associate at the Tyndall Centre for Climate Change Research), helped councils make decisions about where to invest in their flooding and coastal erosion defences.

With one tool, which brought together mapping, economic and flooding data, Cornwall Council could visualise at street level the cost of potential damage resulting from adverse weather events and coastal erosion, providing an evidence base for their investment.

Today, the numerical modelling Heslop (working with Nicholls) is developing is on a much larger scale. Their project aims to understand the impact of sea-level rise on humanity, focusing on the behaviour of the Greenland and Antarctic ice shelves. It is generating sea-level projections to 2500, which they are synthesising with global human population modelling to understand the implications for people under different scenarios such as if we stick to the Paris agreement, continue our reliance on fossil fuels, or somewhere in between.

THE UK'S FIRST SAND ENGINE

In December 2013, a storm surge battered north Norfolk and removed 10 metres of coast in three days. It left the Bacton Gas Terminal a mere 15 metres from the sea and caused severe flooding in neighbouring villages. To protect the terminal and the nearby villages of Bacton and Walcott, Dutch engineering consultant Royal HaskoningDHV were brought in to design a solution.

Having worked on the Zandmotor project, Royal HaskoningDHV created the UK's first sand engine. In 2019, about 1.8 million cubic metres of sand were placed on the beaches flanked by Bacton, Walcott and the Bacton Gas Terminal, to absorb the energy transferred by the sea before it reaches the cliffs and the villages' flood defences.

Two years after the sand was placed, analysis showed that the scheme is working broadly as planned, and is expected to last for 15 to 20 years. Ongoing research has found that the scheme has prevented at least one flood event, helped the local economy by improving the beaches, and reduced worry among those who live in the area.

Contractors depositing sand for the mega nourishment at the beaches flanked by Bacton, Walcott, and the Bacton Gas Terminal © christaylorphoto.co.uk

THE LONG GAME

Erosion is an eternal problem for our island nation. What other tools and technologies are engineers and researchers currently working on to protect our coasts?

Nature-based solutions are gaining traction. For example, planting sea grasses can help stabilise offshore beach nourishments. Similarly, restoring oyster reefs and kelp beds provides another natural defence from erosion. Engineers are even exploring how bacteria can make beach sand more cohesive, and thus less easily eroded.

However, along with the range of engineering approaches in our arsenal, we may need a cultural change in how we see our coastlines, not as fixed lines but as transient spaces.

While we have many ways to manage erosion in the short term, over generational timescales, sea-level rise will eventually make defending some coastal settlements unviable. The government has acknowledged this in recent policy documents and by funding the Coastal Transition Accelerator Programme (CTAP). Focusing on North Norfolk and the east riding of Yorkshire, this aims to ensure coastal communities are supported through these transitions through proactive engagement and action.

For system-wide changes, the slower the change can happen, the less disruptive it will be. Hence, slowing future sea-level rise by mitigating climate change today is the best way to give future coastal communities the time to respond and adapt.

WHERE IS THE SAND COMING FROM, AND HOW CAN WE COLLECT IT SUSTAINABLY?

Sand can be dredged from the sea floor, extracted from inland sites or 'recycled' from spots where it has accumulated near the shore. Unfortunately, some of these methods of extraction, as well as the transport and placing of the material needed for beach nourishment, can have an impact on the local environment. Habitats can be destroyed at extraction sites and take decades to recover, while the activity of dredging itself can disturb marine animals.

In the UK, sand for both nourishments and construction is sourced from areas on the seabed that have been selected for suitability and to ensure limited impacts to the environment, says Jaap Flikweert from Royal HaskoningDHV. This process includes performing a special environmental impact assessment (EIA), which is required by UK legislation for any activities that could significantly impact marine environments.

BIOGRAPHIES

Nicholas Dodd is professor of coastal dynamics at the University of Nottingham's civil engineering department. His research focuses on numerical modelling of beach change because of both natural processes and human interventions.

Robert Nicholls is director of the Tyndall Centre for Climate Change Research at the University of East Anglia and professor of climate adaptation, and previously led coastal engineering at the University of Southampton. Much of his work has focused on sea-level rise and climate change.

Jack Heslop is a senior research associate at the Tyndall Centre for Climate Change Research studying the long-term impacts of sea-level rise on global coastal communities. Previously, Jack worked in engineering consultancy for seven years.

ENSURING ENGINEERING'S ENDURANCE

ENSURING ENGINEERING'S ENDURANCE

Did you know?

- Many lighthouses in the UK and Ireland are still used as physical aids to navigation
- Engineers are investigating structures such as lighthouses and historic railway infrastructure to assess their longevity and preserve them for future generations
- Since the 18th century, offshore lighthouses have been built in a certain way to withstand strong waves, wind and storms

Wolf Rock lighthouse, a 19th-century offshore, rock-mounted structure off Land's End, was the focus of a project looking at the future integrity of such at-risk structures © Alamy

Engineering to preserve a structure or machine can be employed for many reasons, from conserving for historical posterity to ensuring its continued use. Geoff Watts spoke to Professor Alison Raby from the University of Plymouth and Professor Dina D'Ayala from University College London (UCL) about a project to assess the future prospects of offshore lighthouses, which are subject to consistent waves and wind.

Caring for the past requires just as much inventive engineering as building for the future. The application of engineering to heritage conservation rose to prominence in the second half of the 20th century, when the restoration and preservation of everything from steam locomotives to concrete tower blocks began to attract public enthusiasm. However, while the term itself may be relatively new, the approach can be traced back much further. Dina D'Ayala, Professor of Structural Engineering at UCL, points out that in the 6th century AD, Emperor Theodoric the Great appointed a public architect to oversee the restoration of the city walls, aqueducts and other historic structures in and around Rome.

Nowadays, the urge to preserve is stronger than ever. As well as the approach to protecting structures and machines that already exist, preserving them for historic value and prolonging their use, there is also a case to be made for its sustainability credentials. Refurbishing and repurposing structures can be a much greener alternative to knocking them down and building something new in their place. The nature and complexity of some of the challenges is attracting academic interest, with universities possessing the resources required to tackle the issues, as was the case with a project that started in 2016 looking at the structure of 19th-century lighthouses.

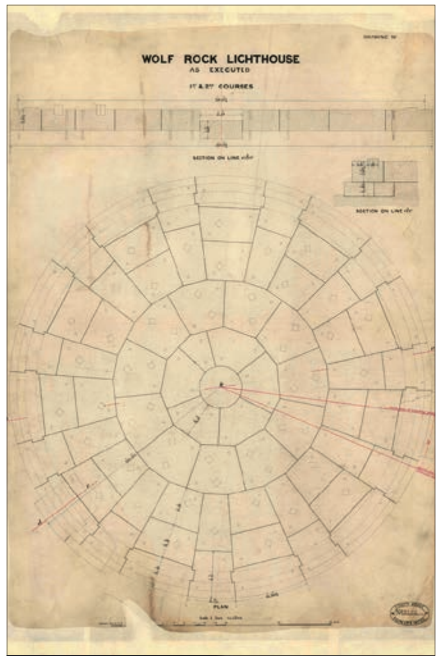
INVESTIGATING VIBRATION

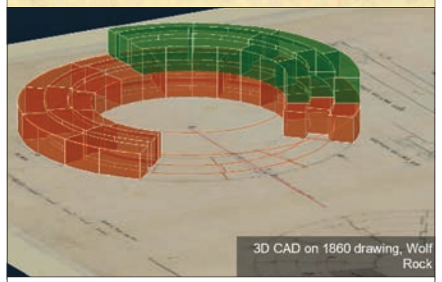
There are more than 250 lighthouses dotted around the UK and Ireland coasts, many of which are still used by seafarers to navigate their course. While electronic navigation techniques such as Global Navigation Satellite Systems (GNSS) and the International Maritime Organization's e-Navigation concept may make it seem that these physical aids to navigation are no longer quite so indispensable to those navigating the seas, lighthouses continue to provide essential services for mariners. They are particularly useful for hazard warning, spatial awareness and confirmation of position, and so the General Lighthouse Authorities of the UK and Ireland (GLA), which are responsible for safe navigation around the British Isles, are committed to maintaining these structures.

More at risk than their onshore counterparts, offshore, rock-mounted lighthouses, such as Wolf Rock off Land's End or Bishop Rock near the Scilly Isles, are exposed to storms. That they have so far withstood the battering of winds and waves can be attributed to their 19th-century construction. Original drawings reveal how the granite blocks forming the circular layers of these towers were not only cut to a precise shape and size, but dovetailed horizontally and keyed vertically to each of their neighbours. This interlocking minimises the risk of slippage between successive layers. "If they'd been designed differently, for example without the vertical interlocking between the blocks, they'd have failed," says Alison Raby, Professor of Environmental Fluid Mechanics at the University of Plymouth. However, with climate change promising more frequent and powerful storms in the future, in 2011 Trinity House – one of the three GLAs in the UK and Ireland – commissioned the University of Plymouth to carry out a pilot study of the Eddystone lighthouse off Cornwall's coast. There had been reports of vibration in the structure, so the project set out to assess the impact of wave loading on it.

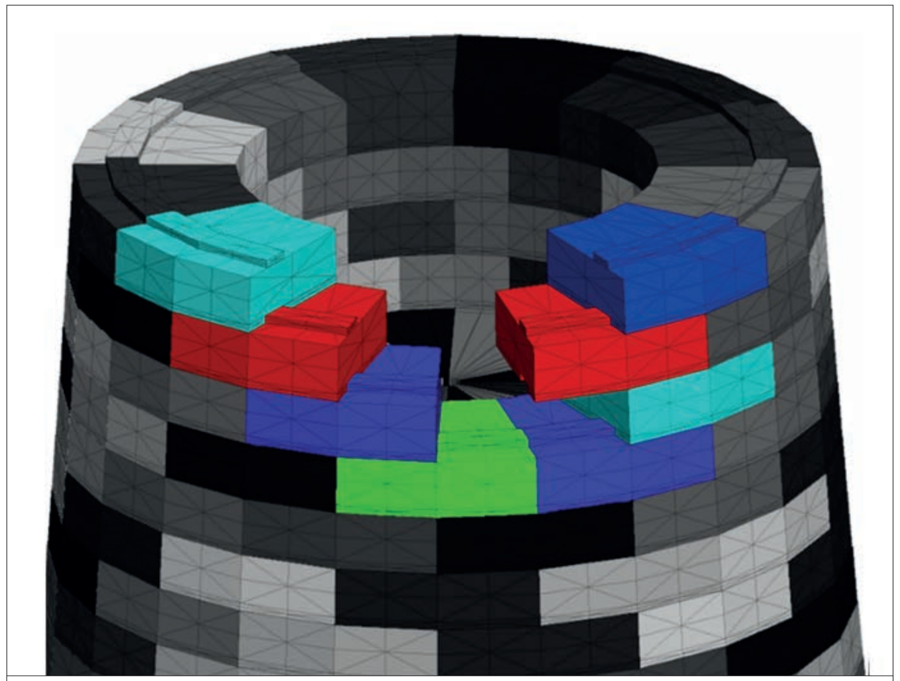
The pilot's findings and methodology were then incorporated into the STORMLAMP project (STructural behaviour Of Rock-Mounted Lighthouses At the Mercy of imPulsive waves), which aimed to investigate the condition of six more exposed lighthouses and discover if they needed any special upkeep measures to guarantee their future integrity. Funded

ENSURING ENGINEERING'S ENDURANCE





Top: original drawing of the first two courses of stonework with vertical peg and pins and lateral keys © Trinity House **Bottom: 3D CAD model shaped from the original drawings in preparation for the structural model**



Discrete element model of Wolf Rock lighthouse. Each stone block is modelled separately, with its complex geometry including the upper and lower keys to simulate the restraint to slide

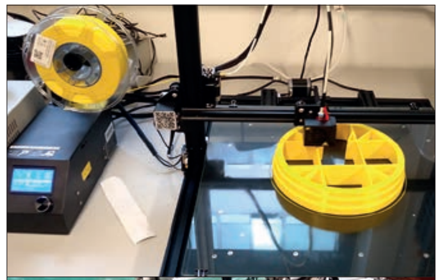
by the Engineering and Physical Sciences Research Council, and led by the University of Plymouth and GLAs, engineers at Plymouth, the University of Exeter and UCL pooled their skills to carry out field measurements, laboratory studies, and analytical and numerical investigations. The project group also worked closely with industry partners including AECOM, HR Wallingford, the Environment Agency, and Atkins.

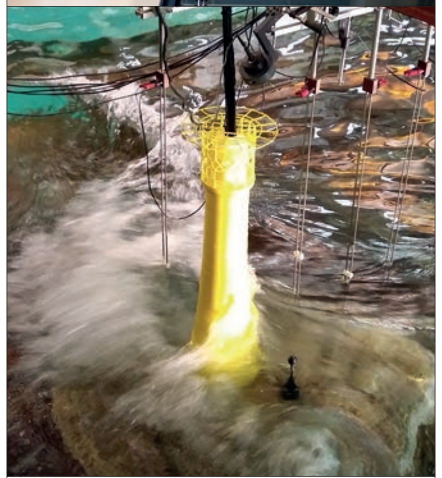
As Wolf Rock is the most exposed of the six lighthouses, it was the focus of the longer-term and most intense studies. Professor D'Ayala and her colleagues at UCL used the details shown in the original construction drawings to create a numerical model of the lighthouse. To develop a realistic structural analysis, they realised that the interlocking design of its individual stone blocks required something more sophisticated than the type of finite element modelling engineers usually employ for numerical structural analysis. This interlocking structure meant that they needed to take account of the lighthouse's rocking behaviour in which, under wave loading, separate courses of the tower's stonework would lift fractionally, but not slide over each other. They were eventually able to create a model that accurately reproduced the discrete nature of the masonry and the possible movement between stones.

STRUCTURAL INTEGRITY

The University of Exeter's Vibration Engineering Section carried out field testing of the lighthouses to assess their structural characteristics. The team set out to determine the lighthouse's dynamic response by using a shaker. This device, placed at the top of the building, incorporated a 50-kilogram weight that jerked back and forth to create a tiny but measurable lateral movement in the tower. Readings from accelerometers, sensors that measure vibration that were placed at several levels in the tower, demonstrated the extent of the displacement. An accelerometer and camera system also monitored Wolf Rock lighthouse, allowing the team to capture data during actual storms.

Professor Raby and her colleagues also carried out physical modelling and laboratory testing focused on Wolf Rock lighthouse. The team collected detailed measurements of the lighthouse and conducted a survey of the rocky outcrop on which it is built – below the water line as well as above it. They then used this data to build a 1:40 scale model. The team recreated the lighthouse in meticulous detail, right down to its 1970s helideck structure at lantern level, which was assembled like an airfix kit. The granite part of the lighthouse comprised 11 3D-printed rings. However, these were not able to tilt and lift with respect to each other. The hollow core of the model housed a





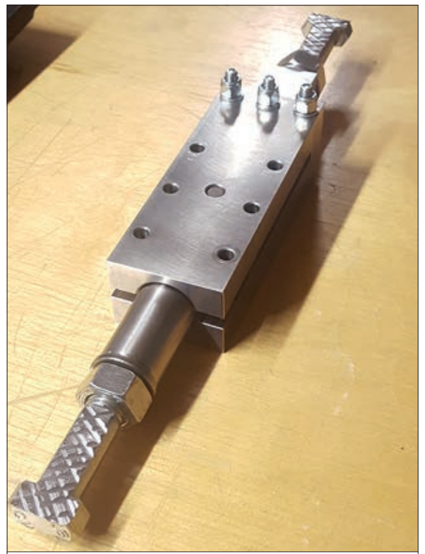
The scale model of the lighthouse consisted of 3D-printed parts and was tested in the University of Plymouth's Ocean Basin © University of Plymouth

six-axis load cell, three accelerometers and 12 pressure transducers. The model was then mounted on its reef and set up in the University of Plymouth's Ocean Basin, where waves of varying intensity crashed into it. The model's sensors allowed the Plymouth researchers to measure the pressures and forces exerted on the structure. This data illuminated the action of the waves on the real lighthouse, and enabled Professor D'Ayala to use her numerical model to predict their likely effect on its integrity.

DURABLE ENGINEERING

The study concluded that, even when taking account of predicted climate change, the lighthouses should retain structural integrity for at least another 50 years without any special interventions needed – a tribute to the foresight of the engineers who built Wolf Rock and other such rock-mounted lighthouses. The STORMLAMP project has offered a template for the assessment of other lighthouses around the world. The vibration testing techniques developed by the University of Exeter had also already been used on other structures, notably bridges ranging from Miller's Crossing pedestrian bridge in Exeter to the Jiangyin Suspension Bridge in China. The project team's findings and experience could also prove valuable to offshore wind turbine design.

PROTECTION FROM EARTHQUAKES



Prototype of the cylinder dissipative device clamped between plates. The device is no bigger than the size of half a brick

Likes waves and storms, earthquakes are another natural occurrence that can place stress on a structure's integrity, causing damage and, in extreme cases, collapse. Since medieval times, a technique using metal tie bars bolted at either end to wall-mounted anchor plates has been used to strengthen buildings and boost earthquake resilience. However, under seismic action the tie bars can fail, or the force of a quake may be such that the anchor plates punch through the walls. About a decade ago, Professor Dina D'Ayala, in collaboration with Cintec International – which manufactures structural reinforcement and anchoring systems – devised and patented an energy-dissipating device. When fitted into the bar at some point along its length, the device enables it to extend, thereby accommodating the shaking of the walls. The device comprises two overlapping surfaces clamped tightly together and held in place by the friction between them. In an earthquake that causes perpendicular walls to move apart, and the tension in the bar to exceed a predetermined level, the device overcomes the friction preventing the relative movement of the two surfaces. They slide over each other and the tie bar lengthens. When the walls resume their previous configuration, and the forces are reversed, the two surfaces of the device are pushed back to their starting position.

The lengthening of the tie bar reduces the likelihood of the anchor plates punching through the walls, and the relative movement of the two friction surfaces dissipates some of the event's energy in the form of heat and work. The device is adjustable, and prior modelling can determine the level of friction and the extent of sliding between the surfaces needed, according to the degree of movement acceptable for a particular building.

Professor D'Ayala and partners developed the system specifically for buildings already in existence so it can be retrofitted, with the tie bars hidden in a floor or in a wall. The system is now patented and in use, and one of the earliest was fitted to a church in L'Aquila in Italy during the reconstruction that followed the city's devastating 2009 earthquake. Professor D'Ayala has since devised and patented an improved version, in which cylinders replace the original flat plate and friction is controlled by using a fluorinated ethylene propylene plastic slip. This makes them smaller and less intrusive, more robust, and smoother in operation.

STORMLAMP has also led to further projects investigating lighthouse structures. To make access to these remote locations easier, many offshore lighthouses have been fitted with helipads: steel frameworks built on top of the original structure. Some of these are past their prime, so Professor D'Ayala's team at UCL and Trinity House recently completed a project to optimise the design of a new generation of helipads. They used a whole life-cycle approach that minimises their carbon footprint and maximises their lifespan, by choosing lighter materials more resilient to the corrosive effect of ocean storms. The reassurance promised by STORMLAMP is not the end of the story for the offshore lighthouses.

BIOGRAPHIES

Alison Raby is a Professor of Environmental Fluid Mechanics at the University of Plymouth, where she leads the COAST Engineering Research Group. Professor Raby is an expert on the interactions of extreme waves with coastal structures and also conducts international post-tsunami reconnaissance missions supported by the Institution of Structural Engineers. She is a Chartered Civil Engineer and Fellow of the Institution of Civil Engineers.

Dina D'Ayala is Professor of Structural Engineering at UCL, where she also holds the UNESCO Chair in Disaster Risk Reduction and Resilience Engineering. She is an expert in historic buildings and the effects of natural hazards. She is a director of the International Association of Earthquake Engineering, a founding member of the International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage, and a Fellow of the Institution of Civil Engineers.

PRESERVING HISTORY

Shildon Coal Drops © The Board of Trustees of the Science Museum Group

All conservation schemes vary, but whatever their size, all raise similar issues: what to preserve, for what reason, and who will pay? These questions are a regular backdrop to the work of conservation engineer Charles Blackett-Ord, whose practice has worked on projects ranging from stately homes to railway bridges.

One such project is the preserving of the Grade II listed Shildon Coal Drops in County Durham – the first UK attempt in 1847 to mechanise the refuelling of steam locomotives. It comprises a six-metre-high arched wall about 100 metres long, which is approached at one end by a sloping ramp that originally supported a length of railway track, along which bottom-opening coal wagons could be shunted. Coal from these would travel down retractable wooden chutes into the locomotives waiting below.

The local council commissioned a survey that recommended extensive underpinning and other work to maintain the structures, which might have cost a couple of million pounds. Blackett-Ord used photographs dating back to the 1920s to argue that a previous buttressing of the wall had eliminated any movement of the stonework for a century. He suggested that a modest strengthening of the foundations would be sufficient to ensure the structure's continuing integrity. The work is now being carried out and guardianship of the coal drop will be with a local museum.

Dunston Staiths on the River Tyne at Gateshead also handled coal. Built in the 1890s and at 500 metres long, it was – at the time – the biggest timber structure in Europe, forming an elevated stage from which to load merchant ships with coal. With the decline of the coal industry these and other staiths were abandoned and fell into disrepair. Dunston Staiths, the largest of those remaining in the UK, are now a scheduled monument. Historic England commissioned Blackett-Ord to carry out a survey of the sections most in need of repair. The subsequent restoration project cost £500,000, but as Blackett-Ord adds, a full restoration of the entire structure might cost £10 million.

The utilitarian argument for conservation relies on sustainability: why erect something new when an old and beautiful building can be repurposed? Reusing rather than renewing has led to redundant churches becoming museums and dockside warehouses turning into apartments. Economics also plays a part; conservation is self-evidently good for tourism, and in this lies part of the case for places such as Shildon Coal Drops and Dunston Staiths. Although neither now serve their original purpose, both attract visitors. Blackett-Ord also offers a less tangible, but no less justified argument for their conservation. "The value of keeping them standing is the same as that of keeping up medieval churches," he insists. "They've got their own historic importance."

KEEPING COMPLEX SYSTEMS ON TRACK

In an engineering career that began with keeping London's underground running, Kuldeep Gharatya FREng was one of the first people to introduce systems engineering to major programmes and the operation of railway systems. He spoke to Michael Kenward OBE about solving complex problems.

There is a significant difference between tinkering with your uncle's car and managing nearly 700 engineers on one of the world's busiest metropolitan railway systems. But that is how Kuldeep Gharatya FREng, Head of Engineering for major programmes in Transport for London (TfL), turned his mechanical engineering qualification into a plan to bring the concepts of systems engineering into modern railway engineering.

Gharatya had a typical introduction to engineering. Maths and physics were always his best subjects at school. However, apart from his brother-in-law, there were no engineering role models in the family. Indeed, he confesses that he didn't have much of an idea of what engineering was about. When it came to a degree course, he wanted to do something useful. "I knew that engineering was quite creative. It was to do with problem-solving, but also rewarding."

As a Londoner, Gharatya looked local and enrolled on a mechanical engineering course at the University of Westminster, followed by a year at UCL studying for a graduate diploma in mechanical engineering. He remained in the city for his first job as a graduate mechanical engineer with London Underground (LU), where he worked to keep trains running and on projects such as the Jubilee Line extension.

A SYSTEMS APPROACH

As Gharatya became familiar with LU, he observed the importance of the different engineering systems needing to

Gharatya (far right) was honoured for The Rail Architecture Framework (TRAK) development at TfL, by the International Council of Systems Engineering (INCOSE)

work together to deliver the required outcome. He began to see how LU could benefit from a systems engineering approach. At the time, this way of seeing engineering projects on a grander scale was relatively new.

Working with different departments he "could see that there was not enough communication between the disciplines". This led to some "siloed thinking", he adds, and this was happening in an increasingly complicated world. "Our signalling systems and trains themselves were becoming more complex. The city itself was becoming more complex. Our ridership was growing at a significant rate. It was unsustainable for us to deliver over four million people a day on a Victorian system without significant investment in the infrastructure. It was a perfect storm of increasing demand, increasing expectations, increasing complexity, and operating at the edge of the performance boundary in a tightly coupled system. We needed to think about this very, very differently."

Gharatya thought that LU could benefit from systems engineering. The concept had been around for about half a century but it didn't begin to take root until the 1990s and had yet to make it into engineering education. In 2004 Gharatya enrolled on a master's degree in systems engineering at UCL's Centre for Systems Engineering. There, he worked with engineers from defence and aerospace companies, such as Boeing, Airbus, the Ministry of Defence, and BAE Systems. "It was great talking to them because it … makes you realise that we all suffer the same challenges. It doesn't matter what the industry is." Gharatya returned to LU and started to embed systems engineering into the organisation. Still a novel idea at the time, it was one of the first rail operators to formally take on the approach with a dedicated team.

When asked for his own potted description of systems engineering, Gharatya replies: "You've put me on the spot." The problem starts with the title. "Systems engineering isn't about just engineering. It's about the whole system, which includes people, the environment... It includes a lot of people who aren't engineers, the people who use the system, the people who funded the system, I could carry on". Gharatya recalls another attempt to explain what he did. "I remember saying, it's like, common sense. But, like my dad used to say … the thing about common sense is it's not very common."

Gharatya admits that he too had started with an engineering focus. He recalls his keynote speech in 2005 when he had concentrated on the importance of systems engineering for transport. Five years on, his view had changed to "it's not about systems engineering, it's about systems thinking". It must start at policy, government, all the way down through to delivery.

His view is that the 'engineering' in the title has held back the adoption of systems engineering for the past 20 years. It made people think "that's just something for the engineers to do, and not for us". Systems engineering demands a fundamentally different approach to projects. He believes in spending as much time as possible "in the problem domain", planning what you have to do, before rushing into "the solution domain". You have to think 90% planning and 10% implementation, "because the cost is in the implementation".

To him the case is obvious. "If you look at major programmes around the world, from nuclear, aerospace, transport, HS2, Crossrail, or the Northern line extension, they are incredibly complex systems. If we hope to deliver them efficiently, effectively, and achieving the outcomes that we originally prescribed, we must be very, very good at systems engineering."

Gharatya soon became recognised as LU's resident systems engineer. "What I'm known for really is helping transport, rail specifically, embrace systems engineering." He became the systems engineer in LU's Engineering Directorate in 2004. Then, Head of Systems Integration and the Systems Engineering Manager of its largest programme in 2007.

Never one to blow his own trumpet, Gharatya does not make grand claims for the billions saved over the years through systems engineering. Instead, he jokes that the benefits have been in reduction or avoidance in cost and time overruns, which, when looking back, is always hard to quantify. He is also modest about his own role and instead refers to his teams when describing the rise of systems engineering at LU.

INTEGRATED ENGINEERING

The work of the systems team came into its own when LU was delivering the Victoria Line upgrade, which would increase the frequency of trains. It had to prevent overheating through the energy used. Heat has been a longstanding issue for the underground, particularly when aiming to run more trains in certain sections. "We were optimising the system in such a way that we were not using the additional power originally forecast and thus weren't generating heat that invariably would need to be removed. We were able to run 36 trains an hour on the Victoria line, one of the most intensive services in Western Europe. This optimisation saved hundreds of millions of pounds in whole life costs and gave an entirely new perspective on trying to understand how to cool the tube."

The engineers could change the operating regime thanks to their ability to build complex models of the network and simulate various strategies for running it. "There's always been some form of modelling and simulation, but we really did push that to ever more complexity, ever more systems, [and] integrating those. Instead of having separate simulation capabilities, we wanted an integrated facility, an integrated simulation capability. Then that was extended to creating 3D virtual environments."

That laid the foundation for the use of virtual reality that allowed engineers to 'walk around' in the environment that they were preparing to build. "They could spot things that didn't feel right," Gharatya explains. This approach came into its own when LU wanted to reline the tunnel between Bond

QUICK Q&A

What inspired you to become an engineer?
The drive to solve complex problems.

What are you are most proud of?
Helping to form some of the highest performing and happy teams!

Who influenced your engineering career? (Favourite mentor?)
I would have to say my mentor and LU chief engineer, the late Eddie Goddard.

What's your advice to budding engineers?
Delivering complex things takes teamwork – but also determination and creativity.

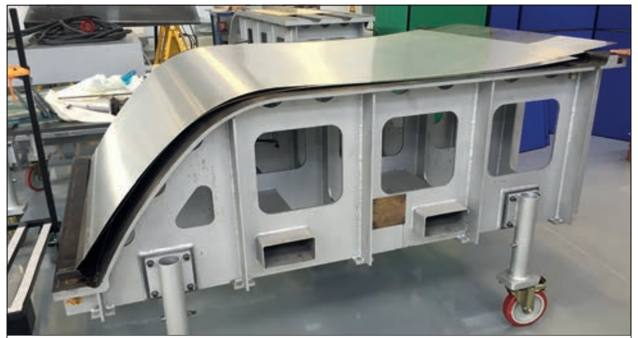
Best bit of the job now?
Developing the leaders of tomorrow and seeing the city change because of our work.

Which record/book would you take to a desert island?
The Beatles Collection and *The Guide to Building a Boat* ☺.

Most impressive bit of engineering to look at?
Well – a vanguard nuclear submarine is pretty impressive when you see it up close!

What do you do in your spare time?
I love playing and watching football.

SLIDING DOORS



A prototype lightweight door for London Underground trains, which TfL engineers developed in partnership with the National Composites Centre. For passengers, the underground system begins and ends at the doors. Lighter doors not only save on energy, they can open and close more quickly, or be made bigger, so that people can get on and off more quickly. Trains with lighter doors can spend less time at the platform, allowing more journeys per hour on a line © TfL

If a systems engineer wanted trains to be more reliable and quicker for passengers to get on and off, the least obvious starting point would be "let's change the doors". However, that's exactly what the team did in one of Gharatya's favourite projects. A decade ago the Department for Transport's innovation team, working with the National Composites Centre in Bristol and TfL's engineers, came up with a prototype lightweight door, which removed a tonne from the weight of a train.

Weight is a key factor for train engineers and has many knock-on effects. Lighter trains don't just save energy, they also save on the cost of track maintenance. Door motors can be an unreliable component of a train. Lighter doors would be more reliable and quicker to open and close.

Lighter doors could also save a couple of seconds on how long the train has to stay in the station, which is worth a lot of money on a high-frequency metro system. Another idea could be to keep the doors the same weight but make them twice as big so that passengers could get on and off more quickly.

Unfortunately, the project also revealed a 'system' challenge when it came to finding someone to make the doors. A key aspect of Gharatya's systems thinking is that it must include the wider supply chain. "We're not a train manufacturer. What we needed was someone to take that leap of faith in the manufacturing side, ideally in the UK." The consortium proved it could be done; the next step was for the supply chain to take that forward in train design, which is yet to happen.

However, the project did help to spread the word about the bigger environmental challenge. "At that point in time not many people were talking about carbon or decarbonisation, If you think about it, saving a tonne per train, whatever train you're on – electric, diesel or otherwise – it is now probably more compelling than it was then."

Street and Baker Street without having to shut down the line (see box 'Open data').

LEARNING FROM OTHERS

When LU became part of TfL, Gharatya took on the role of Head of Innovation, Technical Strategy, System Performance and Engineering Services. The new head of innovation role grew out of the rise of systems thinking at LU. The position was another way of encouraging engineers to look at the bigger picture and see what they could do for the business.

When it came to innovation, LU didn't have a big R&D budget, Gharatya explains, but by drawing on external funding, from Innovate UK for example, it could create consortia of people who could work together. "What was enjoyable was creating those consortiums, often with people that we'd not worked with, people who have not worked in our industry." It was a way of introducing them to a different area of potential growth for their business, he adds. Another innovation at TfL was the rise of international consulting. Gharatya explains that this was a way of exposing TfL's engineers to transport systems and supply chains in other countries. Working in Singapore and advising other cities on their metro systems was a way of "broadening the horizons of the individuals that were involved, leading them to deliver even bigger and better things when they came back".

Gharatya now sees his current role, overseeing major projects, as being to "enable our engineers to deliver the brilliant capital infrastructure that this city needs". Systems engineering is now down to the "brilliant systems engineers who are leading that".

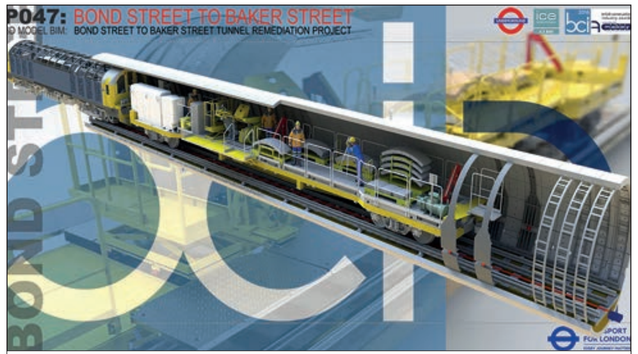
Gharatya has taken on newer tasks. For him, climate change is one of the biggest challenges. "We have a real focus on climate adaptation. That's filtered into the design process. That's something I'm incredibly proud of as an organisation." Again, the aim is to see that 'climate thinking' pervades the system at TfL. "All our engineers have access, and many of them have a full day's carbon literacy training. We've committed to that." Decarbonisation and sustainability are also a part of TfL's corporate targets and programme delivery process.

Gharatya also sees TfL's environmental credentials as crucial to its ability to recruit engineers. "From a skills agenda perspective, it's also become a reason why people would like to join an engineering company." Showing that you take environmental issues seriously is the key to attracting good talent. "The carbon credentials of any organisation will be, I think, a discriminator. If we can show a path to sustainability, not just building things, but improving the environment that we live in, if we can draw that parallel… why wouldn't they want to become an engineer?"

Then there is the added attraction that TfL's rail engineers can see the positive effects of their work. "We have the pull of being in a really exciting place, and people being able to see their efforts actually being implemented." Gharatya puts it in personal terms. "I have helped change the city that I was born in, the city that I love. And some of those changes will be there for a very long time. And that's not me on my own, of course. That's my teams."

Gharatya will soon have an opportunity to see just how universal his views on skills and systems engineering are beyond the rail sector. He will soon change transport modes when he takes up the role of Technical Services Director at NATS, the UK's leading provider of air traffic control services. Again, he sees this in the context of the bigger system, and challenges of cities and mobility. "Those challenges don't just restrict themselves to the physical landscape of a city." The UK has some of the most congested and complex airspace in the world, and inevitably in the future we will see greater use of drones and vertical take-off and landing craft. "We already have some of the best air traffic control systems and people in the world," he says. "But we can't stand still. What we've got to do is understand what that journey looks like in delivering the next phase of modernisation. For me, I think it's going to be an incredibly exciting time."

OPEN DATA



When London Underground wanted to reline the Jubilee Line tunnel between Baker Street and Bond Street it started by creating a digital model of the complex project so that it could work without disrupting the network. The entire programme was designed and run in a digital environment before working on site © TfL

Systems engineering thrives on knowing what is going on. At TfL this means collecting data on the rail network's many different components and systems. Over Gharatya's career he has seen an explosion in the amount of data that engineers can gather and have to manage and understand.

That data is the basis of the modelling and simulation that underpins system engineering. "Instead of having separate simulation capabilities, we wanted an integrated simulation capability. And that was extended to creating 3D virtual environments." In effect, this allows engineers from TfL and its supply chain to walk around in the environment that they were planning to build. "That was brilliant, not only for our customers, but for our operational and maintenance colleagues. They could spot things that didn't feel right."

It went so far as modelling the 'factory' that would do the work. That was designed and run in a digital environment before execution on site, he adds. In this way, the time spent before the work began significantly reduced the time it took to do the work. "It gave us far more confidence in terms of what we were doing."

This approach came into its own during the project to reline the tunnel between Baker Street and Bond Street. Faced with working on a live line, the engineering team designed the entire programme working on a digital twin.

For Gharatya, data must pervade the system so that people at every level of the organisation can understand what is going on. "I don't believe that the data should just be modelled or understood by a team that looks at data."

"I'm still surprised today that data is just not so freely accessible to everyone." TfL was the first to have an open data policy. "We're really proud of that. It's generated tens of millions of pounds worth of value and other cities have followed suit."

One example of where data can have a wider impact was in the Wayfindr project from TfL's innovation team working with the Royal Society of Blind Children and Ustwo, a London-based software company. They worked with visually impaired people who were very technology ready and who believed they could navigate complex transport systems without the need to be escorted. Users received directions on their smartphones to help them find their way around on LU. The project resulted in an open standard. But for Gharatya it was an opportunity to test the concept rather than a technology demonstration. He knew that the rapid progress of technology would enable all manner of innovations. "The concept was the important thing and opening people's eyes, both internally and externally, to what was the art of the possible."

The Wayfindr project helped passengers with visual impairments to navigate the underground system © TfL

CAREER TIMELINE AND DISTINCTIONS

Studied mechanical engineering at the University of Westminster, **1993–1996**. Graduate diploma in mechanical engineering, **1997**. Mechanical engineer, London Underground, **1997–2004**. Systems engineer, Transport for London (TfL), **2004–2008**. MSc in systems engineering, **2006**. SSR Programme, Systems Engineering Manager, TfL, **2008–2011**. Head of Railway Systems, TfL, **2011–2013**. Engineering Director, Transport Systems Catapult, **2013–2015**. Head of Technical Strategy, Systems Performance and Innovation, **2015–2017**. Non-Executive Director, Wayfindr, **2016–2020**. Head of Engineering Technology and Data, Commercial Development and City Planning, **2017–2018**. Fellow, Royal Academy of Engineering, **2022**. Head of Engineering, Major Projects, **2018–present day**.

INNOVATION WATCH

THE CLEAN ENERGY PIONEERS

Green hydrogen is seen as key to decarbonising sectors that can't easily be electrified, such as steelmaking, but there's nowhere near enough of it. UK clean technology innovators Ceres Power could have a solution. Ceres' Dr Adam Bone, Dr Chandra Macauley, and Dr Caroline Hargrove CBE FREng spoke to *Ingenia* about their MacRobert Award-winning technology.

An apprentice at Ceres' Manufacturing Innovation Centre in Horsham © Ceres Power Holdings plc

Green hydrogen is made using devices called electrolysers, which split water using renewable energy. However, these are still so new that we currently only have the capacity to make a tiny fraction of what we need.

Enter UK cleantech company Ceres Power. The company has developed a unique, solid oxide-based electrochemical technology that produces green hydrogen when run in one direction – as an electrolyser – but can also generate electricity when run in the other direction – as a fuel cell.

Many cleantech companies run into problems when trying to scale up their technologies. But Ceres' unique technology has allowed it to focus on the core innovation, while licensing it to global partners such as Bosch. This has accelerated scaling, with Bosch now gearing up towards manufacturing 200 MW of capacity from 2024.

THE POWER OF FLEXIBILITY

In electrolyser mode, steam is introduced to oxygen to make green hydrogen using renewable energy (see page 36 for an explainer on how electrolysers work). In fuel cell mode, the device works almost like a battery but instead of being finite, can be continually supplied with fuel from an external source.

The dual functionality makes the device useful for storing excess renewable energy as a clean fuel, while at the same time able to produce electricity.

In the long term, the plan is to use hydrogen as the fuel. But until hydrogen is readily available, the cell can also run on biogas, gas, and blends of hydrogen and gas. As the infrastructure for hydrogen, including storage and transport, is not yet in place, this flexibility makes the technology a safer bet for manufacturers.

Key to the technology is a special solid oxide electrolyte, a ceramic membrane in the middle of the cell. It's made of a material called gadolinium-doped ceria (more commonly found in self-cleaning ovens), layered on a stainless-steel support.

A 5-kilowatt stack of Ceres' fuel cells
© Ceres Power Holdings plc

This combination has been there since day one of the company, when Professor Brian C Steele spun out the company from Imperial College London in 2001. It's what makes the SteelCell™ robust and relatively low cost compared to competitor technologies. Today, this robustness forms part of the attraction to Ceres' partners.

"When Bosch first arrived, I took a cell, bent it, slapped it on the table, and said, 'OK, let's go and put it in a stack'," says Dr Adam Bone, who is Ceres' Head of Energy Materials. "[If you did that with] a normal ceramic cell, there's no way you'd want to use it."

PROBLEM SOLVING FROM THE START

But getting an operational cell wasn't an easy journey. Ceres had to develop an entirely new manufacturing processes, as ceramic materials conventionally require temperatures that would melt the metal support.

The team had to find a workaround – and they did. As Dr Bone puts it, "the ability to take a ceramic material and sinter it into a dense layer on a metal support, it's something quite revolutionary and… part of our core intellectual property."

"Ceres' bread and butter is solving really hard problems," adds Dr Chandra Macauley, who is a senior materials scientist at Ceres.

Dr Bone recalls how the company nearly failed in 2012, when Ceres had been planning to do everything, including manufacturing. The company changed tack but fundraising enough to cover its R&D activities was difficult at the time. "We went from 180 people down to 50," he says. Turning the corner took a new vision, new owners and the right business model. "That in itself is one of the biggest challenges, I think, for any startup."

Dr Macauley goes on to explain how collaboration between a whole range of scientific and engineering disciplines has been key to Ceres' success. "That's where so much innovation happens."

"We've got the whole kind of gamut of engineering working on this problem," says Dr Bone.

EQUIPPED FOR THE REAL WORLD

Ceres has been recognised for its persistence, ingenuity and years of hard work with the Royal Academy of Engineering's 2023 MacRobert Award. The award also shines a light on the significant need for Ceres' electrolysis technology.

"Climate change is now. It's not in the future – it's now. We have to take those chances," says Dr Caroline Hargrove, the company's Chief Technology Officer. She explains how Ceres decided to raise more money to get the electrolyser functionality working, even though the fuel cells were ready for the market. "We knew that we needed to get going… because [the technology is] needed today."

Ceres is working hard to create a market for its electrolysers and "[help] users use it". This is because hydrogen has teething problems yet to be ironed out – such as how to store and transport a gas that's lighter than air without it escaping.

The company's first electrolyser, a one-megawatt demonstrator, will be installed in a technology park in Bangalore by the end of the year. "For hydrogen, you need to think where you're going to store it, how you're going to compress it – have you got the infrastructure?" says Dr Hargrove. These are the sorts of questions the demonstrator intends to answer.

Meanwhile, Bosch fitted a pilot fuel cell system at a bus station in Germany that has been producing electricity and feeding it to the grid for nearly three years. The heat it gives off is enough to provide heat and hot water to a bakery in the station. While it currently runs on gas, it is a way to prove the technology works before hydrogen becomes widely available. Its CO_2 emissions are also lower than traditional combustion at gas power plants, and much purer, so they can be captured for industrial processes.

Ultimately, the company envisions the fuel cell as a small-scale, off-grid power source: a secure energy alternative for data centres or charging stations for electric vehicles. As electricity demand rises due to electrification, Ceres hopes the technology will help relieve pressure on the grid.

The company is clearly taking a lot of steps in the right direction to get its technology out there – and not just in Europe, but also in South Korea and China.

"Climate change is obviously a worldwide problem, and we have partners now all around the world," says Dr Macauley. "Because we need scale in order to solve this problem in the amount of time that we need to solve the problem. And quite honestly as a scientist working on it, it's tremendously empowering."

EYES ON THE INNOVATORS

***Ingenia* is keeping a close eye on the startups using their engineering know-how to disrupt the status quo.**

Wootzano has launched its labour-saving fruit-packaging robot in the US

Clinical trials have started on **Affectronics**' deep-learning-based technology, which alerts clinicians to pain in premature babies

Researchers are testing **Milbotix**'s smart socks at a care home – they detect levels of anxiety and distress in people with dementia

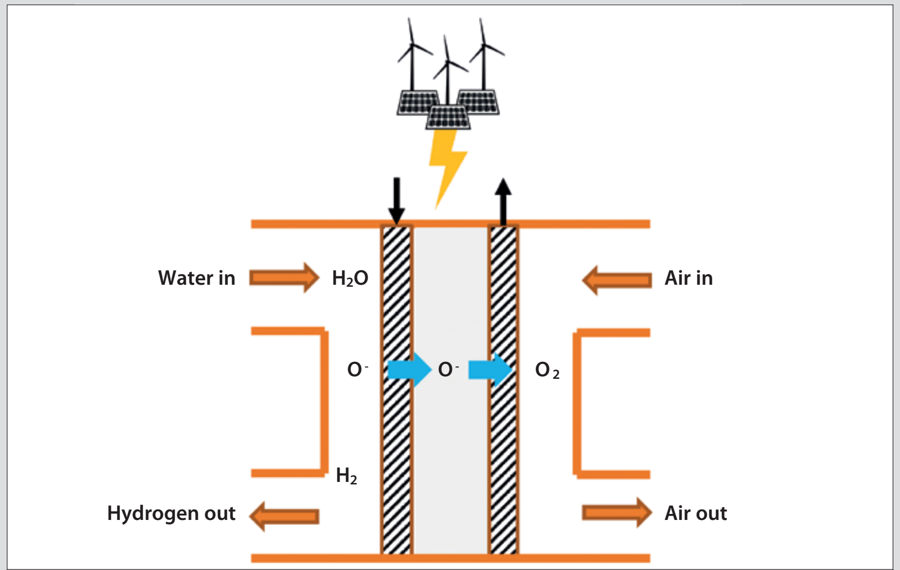
Go Eve has raised £3 million to take its multiple electric vehicle charging system to market

Exergy3 has received £3.6 million to test its technology for decarbonising industrial processes: first up, a carbon-neutral whisky

HOW DOES THAT WORK?

ELECTROLYSERS

Green hydrogen can play an important role in helping us to meet net zero. It is created when hydrogen is extracted from water using renewable energy.



The process of splitting water into hydrogen and oxygen in a solid oxide electrolyser © Ceres Power

Electrolysers are electrochemical devices that use electricity to split water into hydrogen and oxygen, a process known as electrolysis. When electrolysis is powered with renewable electricity it produces green hydrogen, which is now widely recognised as key to enabling the energy transition.

As with other electrochemical devices such as batteries and fuel cells, electrolysers consist of an anode and a cathode separated by an electrolyte. Electrolysers function in different ways depending on the type of electrolyte material and the ionic conductor. Examples include alkaline, polymer electrolyte membrane (PEM), and solid oxide electrolysers.

Alkaline electrolysers are the most widely available. The electrolyte is a liquid alkaline solution of sodium or potassium hydroxide and the electrodes are coated metal wires. Applying a current to the solution causes water molecules at the cathode to gain electrons. This splits them into hydrogen gas and negatively charged hydroxide ions. Hydroxide ions move through the electrolyte from the cathode to the anode, where they lose electrons back to the circuit and form oxygen gas and water molecules. This technology has proven to be reliable and low cost.

PEM electrolysers use a very thin polymer membrane as a solid electrolyte. Water reacts at the anode to form oxygen and positively charged hydrogen ions, which then move across the PEM to the cathode. Electrons flow through an external circuit to the cathode, where they combine with the hydrogen ions to form hydrogen gas. The technology processes more power in a smaller space and can adjust its output depending on the electricity available. Coupling PEM with intermittent renewables makes sense where operators are prepared to pay a higher price for dynamic response and a compact footprint.

Solid oxide electrolysis (SOEC), such as that developed by Ceres Power [see page 34], is a high-temperature technology that uses a solid ceramic electrolyte. Steam at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions. These ions pass through the solid ceramic membrane, forming oxygen gas at the anode and generating electrons for the external circuit. It is about 25% more efficient than incumbent low temperature technologies and can make use of residual heat from industrial processes. While best-in-class alkaline or PEM technology would require about 50 kWh of electricity to produce a kilogram of hydrogen, SOEC only needs 37 kWh of electricity.

Green hydrogen can be turned back into electricity when demand is high (potentially through a fuel cell, essentially an electrolyser in reverse). It can also be used as a precursor to other sustainable fuels where higher energy density is required, such as in shipping or aviation. Methanol, ammonia and methane can all be synthesised from hydrogen and are being considered as future energy carriers and in zero carbon power generation.

While the debate continues about the full extent of global hydrogen applications, it will be key in decarbonising essential but emissions-intensive industries such as steelmaking, cement and marine transport. Evidence is also growing for a major role in long-term energy storage for renewables. Electrolyser technology can play a significant role in reaching net zero.

Companies around the world are increasing electrolyser production, green hydrogen plants are under construction, and the industry is transitioning from pilot to industrial projects. As with solar, wind and battery technologies, these actions will be key to driving the scale needed to reduce costs and ensure we get electrolysers from being tomorrow's technology to part of the infrastructure of our society.

Words by Ceres Power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