Tomorrow's Engineering Research Challenges

Visions from the UK Research Community

Convened and facilitated by

UKRI Engineering and Physical Sciences Research Council

Co-chaired by
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The scientist discovers a new type of material or energy and the engineer discovers a new use for it.

Gordon Lindsay Glegg's quote is a huge simplification, but it speaks to the vital role of engineering in connecting discovery science into innovation and solutions to the practical challenges facing our society

Engineering is crucial to translating the frontiers of knowledge into disruptive new technologies and creative solutions which can transform the world around us, improve our lives and strengthen economic prosperity. The UK has a deep and broad research base with demonstrable excellence across many areas of engineering, but we need to take this to the next level if we are to raise our research ambitions and become a genuine science scientific superpower and innovation nation.

I hugely welcome this report on Tomorrow's Engineering Research Challenges and wholeheartedly support the recommendations.

The government's UK Innovation Strategy, published last year, sets out our long-term plan for delivering innovation-led growth, and highlights how engineering is of fundamental importance in achieving this. A key lesson from the pandemic was the need to bring discovery and engineering side-by-side, and **Tomorrow's Engineering Research Challenges** outlines how the UK's outstanding engineering research community can achieve this. The new five-year UKRI strategy also outlines how the funding of UKRI and its councils, such as EPSRC, will be key to delivering our ambitions for the UK as a global leader in research and innovation. With these strong foundations in place, there is also a need to continue to look beyond the horizons of the immediate future to ensure that our next generation of scientists and engineers can think in different ways to ensure we are on the front foot for future technological and societal revolutions.

This report combines diverse views that recognise the need to allow our world-leading researchers to follow their curiosity to tackle grand challenges and complex societal problems through engineering, accommodating a broad span of interdisciplinary and inclusive approaches and forming new connections, collaborations and networks alongside delivery outcomes for industry and society. Engineering research is the route to explore and equip us for this sustainable and hopeful future and make an innovation nation a reality. It is key to realising the benefits of space research for our quality of life on Earth; to embed systems approaches to improve healthcare or to accommodate safer adoption and use of technological solutions to tackle the barriers to inclusivity in society.

I look forward to the benefits that arise from the implementation of this report, which will allow our world-leading research community to tackle our planet's greatest challenges now and in the near future. I would like to thank Professor Dame Helen Atkinson and Dr Peter Bonfield for independently co-chairing this important initiative and for bringing the voices of the community together with the support of EPSRC.

The urgency of the global challenges we face demand both world class discovery science and the creative, problem-solving ingenuity of our engineers to develop practical solutions.

George Freeman MP
Minister for Science, Research & Innovation
6 July 2022

Chief Scientific Advisor, BEIS

I really welcome this report on Tomorrow's Engineering Research Challenges.

As the report states, engineers are vital to the future of the UK. I thank the co-chairs of the report, Dame Helen Atkinson and Dr. Peter Bonfield for their engagement with the cross-government network of departmental Chief Scientific Advisers.

Many of the recommendations in the report absolutely chime and resonate with issues raised by the departments. We see throughout the report the vital role engineers are going to play in delivering Net Zero. Engineers can bring a system of systems understanding, which is going to be critical to meet the challenges of achieving net zero by 2050.

I hope the report really does help UK engineering continue to flourish and grow, to provide the solutions to tomorrow's engineering research challenges.

Professor Paul Monks
Chief Scientific Advisor
Department of Business, Energy and Industrial Strategy

Foreword from the Executive Chair, EPSRC UKRI

I am very pleased to welcome this report from our community. It is an open and honest reflection from our key stakeholders and I would like to thank all those who have been involved, including our co-chairs Helen Atkinson and Peter Bonfield.

We are living in unprecedented times; it is now more important than ever for us to think of the challenges of tomorrow and how research and innovation will allow us to overcome these.

The Tomorrow's Engineering Research Challenges report is extremely timely. EPSRC UKRI has now set out its initial funding plans for the next 3 year Spending Review period, and these already include many of the priority areas identified in this report. By being on the front foot as far as science and technology are concerned, we can support the ideas, skills and innovations that are needed for a sustainable, resilient, and prosperous UK.

It has been great to see the community connect and collaborate to identify the key challenges for future engineering. The new perspectives that have been offered have been refreshing and have truly shaped our thinking in the development of this report. EPSRC UKRI is committed to working with the engineering community to realise their recommendations. Engineering skills are essential to deliver the innovation and new technologies required to deliver social and economic success across the UK.

Professor Dame Lynn Gladden DBE FREng
Executive Chair of the Engineering and Physical Sciences Research Council

Foreword from the Co-Chairs of Tomorrow's Engineering Research Challenges

In our work on Tomorrow's Engineering Research Challenges over the last nine months, we have taken an inclusive approach and engaged with wide and diverse communities.

We have listened hard. This report, which is evidence-based, represents the outcome of that listening. It is not exhaustive, but it does highlight significant opportunities for UK engineering research to play an even more major role in addressing the critical challenges facing the UK and the world. To have that impact requires a step change in how collaborators are connected, how research funding is deployed and how bids are assessed. Engineering research and development needs to be less exclusive and siloed, and more open, inclusive and integrated both across the engineering disciplines and into the socio-technological realm.

Our work has led to some clear recommendations on making engineering research more inclusive and enabling greater impact to be achieved. We identify important high-level priorities, critical cross-cutting themes and ambitious technological challenges. Together these give a framework to consider and implement that will enable significantly greater integration, impact and value for every pound invested. This, in turn, will help grow and position further the UK as a major engineering force for good in the world.

The wide engagement during our work has been utterly inspiring and informative. There has been huge enthusiasm to contribute. Our approach has enabled safe and inclusive conversations and debate to take place, from a diverse array of people at all career stages and from within engineering organisations and more broadly.

Together they and we have built a positive movement for improvement that now can be extended to create an integrated force for change.

This will build further on the esteem in which UK engineering research is held worldwide.

We would like to thank the superb contributions and generous gift of time from our many contributors. Andrew Lawrence and the team at the EPSRC have facilitated this whole engagement process and carried out outstanding work enabling this report to be produced.

We commend the recommendations in this report. It is the time for positive disruption and action to make them a reality.

Professor Dame Helen Atkinson DBE, FREng
Pro-Vice Chancellor, School of Aerospace, Transport Systems and Manufacturing
Cranfield University

Dr Peter Bonfield OBE FREng FIET
Vice-Chancellor and President
University of Westminster

Executive Summary

Engineering is of vital importance to the UK. As an academic discipline it has grown significantly over recent years and the UK remains in a world-leading position in terms of academic excellence and thought leadership. The UK continues its reputation as a melting pot of engineering ideas and innovation.

It is a diverse area that translates many ideas into reality and has potential to tackle every part of daily life and solve our greatest problems; to mitigate the immediate consequences of climate change; to provide sustainable alternatives to our dwindling resources, and to generate resilient solutions to global health crises. Arguably it is now more important than ever that UK engineering talent is harnessed, in collaboration with others, to address the challenges affecting our world.

Tomorrow's Engineering Research Challenges (TERC) is a UK-wide community engagement activity that has been initiated by the Engineering theme at EPSRC. It aims to identify the most important challenges that face engineers in the over the next 10-15 years and to explore the creative engineering research that is needed to tackle these challenges. The key outcome from this activity is to inform and inspire future research strategy for a variety of audiences, primarily EPSRC as the main funders of engineering research, but also other parts of UK Research and Innovation (UKRI) and funders of research, universities, professional engineering institutions, policy influencers in government and researchers themselves.

This initiative is arguably one of the largest engagement exercises performed with the engineering research community. The process of engagement has been undertaken over a nine-month period through various engagements including a series of workshops, roundtable meetings and written contributions involving representatives from academia, industry, professional engineering institutions, early career researchers, EPSRC-sponsored PhD students, engineering equality, diversity and inclusion groups, international representatives and UK Government chief scientific advisors.

The report summarises the key findings taken from that dialogue in the form of a spectrum of challenges presented at different levels: High-Level Priorities, Cross-Cutting Themes and Technological Challenges (see Figure 1).

The High-Level Priorities highlight the most pressing actions for the wider engineering community to enable researchers to address future challenges, including the need for inclusive approaches to engineering, mechanisms for multidisciplinary and interdisciplinary research and the promotion of diverse, agile and impactful skills.

Seven Cross-Cutting themes were extracted from our engagements, where engineering and engineers have a key role to contribute across all sectors and technologies, such as achieving Net Zero and sustainability, faster digital design, understanding complex systems and increasing human resilience.

Finally, and importantly, the focus turns to eight Technological Challenges, derived predominantly from the series of workshops. These ambitious challenges describe where novel approaches and creative engineering research will be vital to make progress across specific domains: space, transportation systems, materials, health and wellbeing, robotics and AI, responsible engineering, nature-based engineering and global engineering solutions. Whilst presented in isolation, there are profound interconnections between these challenges, as illustrated in Figure 2.

In describing the three levels of challenge, this report intends to convey the voice of the community to raise awareness of these challenges and provoke further thought and conversation beyond this initial engagement exercise. The recommendations that have been drawn out from this exercise reflect the challenges presented and aim to stimulate further action for a variety of audiences, to enable these challenges to be addressed. They also serve to positively impact the wider community and future-proof engineering as a discipline. Above all, it is imperative that these actions are progressed in collaboration with the community in an inclusive way, so that we are all able to support our next generation of engineers in advancing innovative engineering solutions for a more sustainable and resilient future.

Tomorrow's Engineering Research Challenges

HIGH LEVEL PRIORITIES

- Promote inclusive engineering outcomes for all with more diverse input
- Strengthen mechanisms to facilitate and fund multidisciplinary andinterdisciplinary research
- Re-engineer the discipline of engineering
- Convene and connect with the professional engineering community to enhance impact
- Encourage diverse, agile and impactful skills
- Inspire the next generation

CROSS-CUTTING THEMES

- Achieving net zero and sustainability
- Faster digital design
- Greater access and use of data
- Increasing human resilience
- Understanding complex systems
- Harnessing emerging, disruptive technologies
- Underpinning tools and techniques

TECHNOLOGICAL CHALLENGES

- Ensure **space research** is sustainable, and design and develop technologies that will be used to explore and sustain life in space and on Earth.
- Develop sustainable, integrated, and equitable **transportation systems**.
- Accelerate environmentally sustainable and socially responsible creation and utilisation of **materials.**
- Improve **whole-life health and wellbeing** by developing sustainable, inclusive, and resilient healthcare systems and technologies.
- Co-design and embed **robotics and AI** into engineering while ensuring ethical use with transparent and equitable decision making.
- Foster **socially and environmentally responsible approaches to engineering** guided by our understanding of human behaviours and needs.
- Unlock the full potential of **nature-based engineering.**
- Deliver adaptable **global engineering solutions** that are compatible with our understanding of the planet's ecosystem.

Figure 1: Summary of Tomorrow's Engineering Research Challenges.

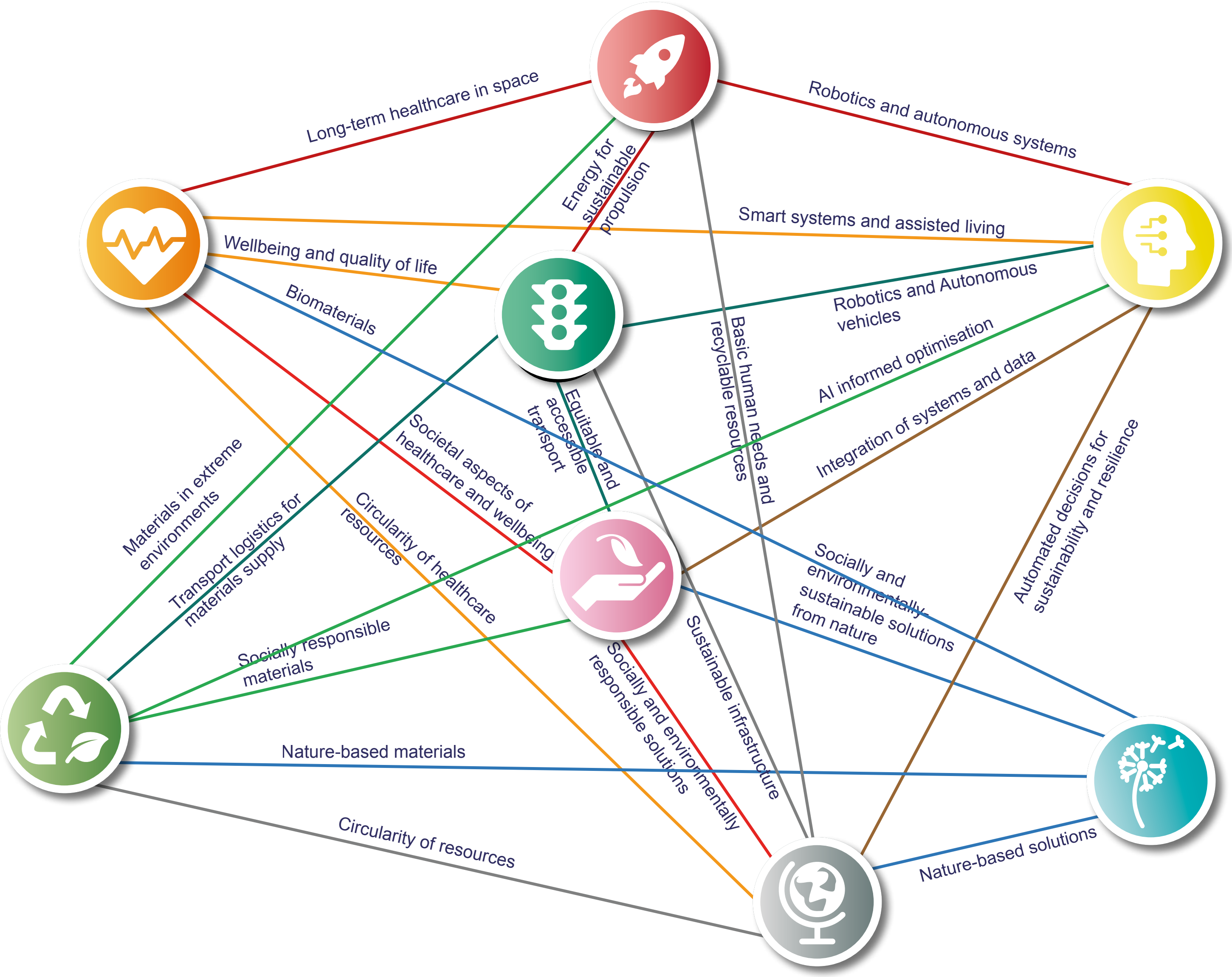

Figure 2: Representation of some of the key interconnections between the Technological Challenges, as identified through our workshop process.

Recommendations

1. Promote inclusive engineering outcomes for all with more diverse input

Our consultation involved diversity in many forms, including specific engagement with representatives of engineering Equality, Diversity and Inclusion (EDI) groups. We strongly recommend continuing effective action by UKRI and associated bodies to improve EDI in the research and development community and to empower inclusive engineering. Inclusive engineering is the discipline of ensuring that engineering products and services are accessible and inclusive of all users and are as free as possible from discrimination and bias, and work for everybody ensuring no-one is left behind. For the engineering research community, inclusive engineering involves considering diversity of inputs and making sure that engineering outcomes are inclusive for all. What this means is that engineering solutions should work for everyone, from every social class, every background and wherever you are in the world.

Specifically, we recommend:

1.1 Adopting the principle that all future research endeavours embrace inclusive engineering outcomes;

1.2 Continuing to strengthen relationships with professional engineering institutions (PEIs), Royal Academy of Engineering, industry and academia to facilitate mechanisms for research which are derived using a diversity of views and inclusivity of inputs (e.g. those applying for funding);

1.3 Increasing opportunities and incentives to form new collaborations;

1.4 Making inclusion permeate through the whole of the research framework, informed by an understanding of good EDI practices and the lived-in experiences of minority groups;

1.5 Making further reaches beyond the established advice routes the norm, to draw in even more diverse perspectives;

1.6 Improve the funding model across funders to ensure high-quality research programmes are funded and distributed throughout the UK.

2. Strengthen mechanisms to facilitate and fund multidisciplinary and interdisciplinary research

A strong message that ran throughout our engagement was that many of the challenges identified are global, socio-technological in nature and cross many different disciplines. Thus, there is need for our engineering research community to address these by breaking down traditional siloes and enabling truly multi and interdisciplinary research. We strongly support the new UKRI strategy on interdisciplinary research and commend its rapid adoption. Specifically, we recommend:

2.1 Proactive support mechanisms to ease, facilitate and fund interdisciplinary and multidisciplinary research;

2.2 Enhancing the ability to identify and fairly assess interdisciplinary research ideas;

2.3 Encouraging the engineering community to engage with interdisciplinary challenges, specifically by integrating with and involving expertise from social and environmental sciences.

3. Re-engineer the discipline of engineering

Some of the key messages from our consultations are that engineering challenges have a strong socio-technological dimension and engineering should be seen as a method to effectively transition science into solutions. As we have heard from our engagement, there is a lot of commonality in the problems identified by the engineering community with other disciplines, where a broader appreciation of skills, ideas and application is vital to derive creative solutions for tackling them. This presents an opportunity to future-proof the discipline of engineering to complement important interdisciplinary practices. Specifically, there needs to be a shift to expand the traditional view and remit of engineering to accommodate more societal and environmental considerations and creative practices. Critical to this shift is a greater appreciation of the ethical considerations of engineering solutions. There is a benefit in combining aspects of science with engineering and expanding engineering boundaries to ease the ability for engineers to ethically address integrated and complex challenges, and continually reinforce our standing as a research superpower. Specifically, we recommend:

3.1 That the PEIs work in collaboration with UKRI, universities and education providers to enable engineers to adapt to future needs, seize opportunities to expand their skill-sets and be open to broaden traditional boundaries to future-proof the discipline.

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4. Convene and connect with the professional engineering community to enhance impact

Building on and maximising the benefits from each of the communities we have engaged with through this exercise is important. Engineering research funders and associated bodies, such as the professional engineering institutions (PEI's), should accept collective leadership in motivating key communities to share knowledge and ensure the UK's engineers are appropriately skilled; maximising the relationships gained and ensuring that challenges are taken progressed in unison. Their strong convening power and leverage (e.g. from industry members) help to maximise and accelerate impact. Furthermore, longer term challenges require an international scale of research and standards. Thus, we should build better links with international research organisations to solve the challenges of tomorrow. Specifically, we recommend:

4.1 Forming and strengthening regular gatherings of UKRI, PEI's and learned bodies, other funders and third sector to share strategies and knowledge;

4.2 Re-convening diverse members of the community on a regular basis to revisit and refresh long-term engineering challenges;

4.3 Creating methods to facilitate networks to ensure wider research communities, including international research organisations, can connect effectively.

5. Encourage diverse, agile and impactful skills

People are key to addressing Tomorrow's Engineering Research Challenges. We strongly commend existing professional development schemes to help develop researchers and technicians of the future. We further recommend strong emphasis, in an incredibly competitive marketplace, on providing greater support for diverse communities so they are connected to technological challenges, whilst bringing together training and talent in an inclusive, cohesive and flexible way. There is a role in influencing how PhD programmes are connected to technological challenges through research training. The PhD community should also be supported to be inclusive, cohesive and flexible. Specifically, w e recommend:

5.1 PEI's to continue to work with the Engineering Professors Council, UKRI and education providers to ensure a pipeline of people with diverse, agile and impactful skills at all career stages, through continuing professional development;

5.2 Creating more opportunities for early career researchers to come together to share best practice and influence future research agendas in the eight Technological Challenge areas identified in this report, with the early career community putting its own energy into facilitating this;

5.3 Encouraging an engineering CDTs annual conference to bring together and share knowledge and understanding towards inclusive and sustainable engineering careers, with the PhD community itself leading on this with support from the EPSRC and its collaborating bodies;

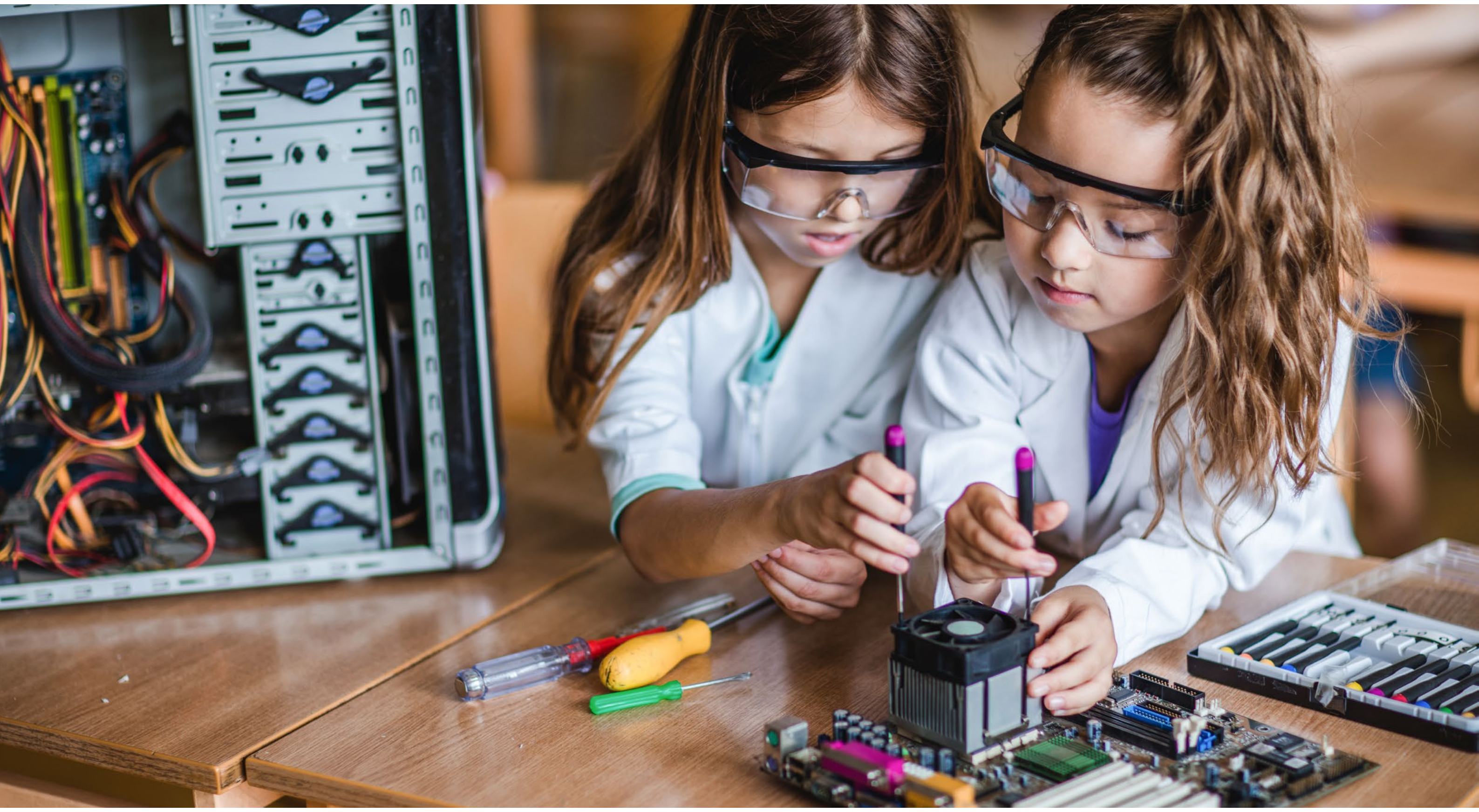
5.4 Embracing and prioritising key areas of skills-needs such as sustainability, digital skills, systems thinking, data science and new emerging technologies such as AI and robotics.

6. Inspire the next generation

Through our engagements, there were clear messages of the important responsibility to encourage young people into engineering and elevate public appreciation by showcasing how engineers can contribute to a better, more sustainable future. UK engineering research and development allows the freedom to be creative and can be an incredibly rewarding career. Funders, professional bodies, universities and industry should support researchers and the existing workforce to further inspire and attract young people into engineering careers and continue to reflect how engineering is represented in the compulsory curriculum and in wider society. This should be complemented by promoting responsible innovation and inclusive approaches to interactive public engagement and empowering our communities to interact with society.

Specifically, we recommend:

6.1 UKRI, Professional bodies, Universities and Industry place their weight behind outreach on future engineering challenges and supporting the research community to do the same; they should engage in a public dialogue around the eight Technological Challenges to elevate and update the valuable contribution that engineering and engineers make to a more sustainable future.



7. Integrate, develop and progress outcomes against each of the seven Cross-Cutting Themes

Our engagement has highlighted that engineering research has a vital role to play in supporting the government drive to achieve net zero and sustainability, as well as enable faster digital design to improve productivity, enhance access and use of data to inform solutions, improve our resilience and to understand complex systems. Furthermore, engineering has a strong part to play in the translation of emerging technologies (such as the Transformative Technologies highlighted in the UK Government's Innovation Strategy) providing we continue to underpin our research endeavours with the right tools to enable our researchers to flourish. In supporting these areas, we recommend:

7.1 Calling on the wider Engineering community to proactively engage with the Cross-Cutting Themes identified in this report;

7.2 Encouraging research and skills funders to support the development of researchers to address these Cross-Cutting Themes and enable the development of science, tools and techniques to support them.

8. Develop and progress outcomes against each of the main eight Technological Challenge areas.

The Technological Challenges identified by the community highlight important areas where engineering can provide novel solutions in 10-15 years. Whilst some work in these areas is already in progress and chimes with current UK Government strategies and priorities (e.g., Space, Transportation Systems, Health and Wellbeing), our recommendation is to continue to advance and deepen the thinking around the Technological Challenges and to do this with an inter-disciplinary, global and inclusive mindset. It is also important that these are openly communicated to a wide, diverse community to rapidly advance the research and create solutions. Specifically, we recommend:

8.1 EPSRC, UKRI and associated bodies review the report, and continue to involve the wider community, including those engaged with here, in the engineering challenges identified and co-create solutions with them. Focussed activities to develop the themes are key and should include exploring the synergies of existing portfolios; connecting and mapping opportunities to maximise integration and impact of the research, and aligning research and innovation activities and mechanisms towards them.

Additional Recommendation

9. Support the flexibility of funding approaches

Our consultations emphasised the need to allow the freedom for researchers and research teams to solve Tomorrow's Engineering Research Challenges. There is a great desire for flexibility in funding approaches to optimise support for discovery-led and application-driven research to strengthen the generation of new ideas and multidisciplinary activities, and to support the translation of research into application and industrial uptake, with particular demand for schemes which span from Technology Readiness Level 1 through to 6. Specifically, we recommend:

9.1 Promoting opportunities for the community to have the freedom to innovate;

9.2 Continuing to prioritise funding for community-led research both in discovery-led and application-driven modes within funding models;

9.3 Strengthening industry buy-in to support the translation journey and partnering with them from an early stage.

Introduction

The world in which we live and work today has been shaped by engineering.

From the very beginnings of civilisation, humans have applied our increasing knowledge of the laws of nature, gravity, thermodynamics and the atom to design and build tools and create solutions to solve some of our greatest problems. The contribution of Engineering is clear to see in the provision of basic human needs; from the food we eat, the water we drink and the buildings we live in. It has transformed the way that we travel, how we communicate and how we diagnose and treat diseases. Engineering is the process by which we, as a society and as a species, modify our environment to suit our needs and wants. Almost everything we rely on in today's world is a product of engineering.

Engineers are at the heart of solving the world's problems, enabling solutions and lowering barriers through more complex and creative solutions. However, whilst engineering has enabled humankind to flourish and grow, over the past 250 years the impact of engineering has arguably also had a negative impact by drawing on our planet's precious resources, increasing the consumption of energy and emitting greenhouse gases at the expense of our environment. This has manifest in urgent planetary needs that require new, bold and creative solutions to address. It is right that Engineers can adapt and realise solutions through novel research and application, but also to adapt their ways of working to collaborate with others to drive forward progress for a sustainable, inclusive and equitable future.

The time for action is now.

Why now?

There is a global appetite for change to steer us towards a zero-carbon future, become more resilient to health crises and reduce inequalities across the world.

In recent years we have seen some dramatic disruptive events, such as the climate emergency, the Covid-19 pandemic and world conflict. These events have changed our way of life and altered our global economy. In these instances, we have mobilised our historical foundation of world-class science and engineering to provide rapid deployment of solutions, such as vaccines, defence measures, alternative fuels and an increase in food and energy security. This has inspired us to think more carefully about how we can harness UK talent in engineering and science to tackle future challenges and the vital role that engineers can play to provide sustainable solutions.

Tomorrow's Engineering Research Challenges (TERC) is a UK-wide community engagement activity that has been initiated by the Engineering theme at EPSRC. The aim for this activity was to capture a diverse range of thought from across the UK engineering research community, to identify the most important questions and greatest challenges that face engineers in the future, and to explore some of the concepts, new approaches and creative ways of working that will be required to solve them. Whilst we have set a timescale of 10-15 years for impact, there is the need to start this work now, so that we contribute to the long-term sustainability of engineering research and skills and enable the next generation of engineers to be on the front foot for future revolutions be they industrial, environmental, economic or societal.

What did we do?

This initiative is arguably one of the largest engagement exercises performed with a diverse sub-sample of the engineering research community.

The intention was to capitalise on our world-leading research base and bring together thought-leaders, influential advisors and enthusiastic experts across UK academia, industry and wider stakeholder groups to contribute their own insights and perspectives. EPSRC convened and facilitated a focussed engagement process designed to extract creative ideas, identify key challenges and reveal future opportunities through a sequence of activities:

- **The TERC Workshops** – These facilitated virtual workshops, held in November and December 2021, harnessed the views of a selection of the research community to unlock key technological challenges and ambitious research ideas. The participants spanned a wide range of disciplines not only from engineering but also mathematics, physics, chemistry, biology, environmental science, humanities, design, economics and social science. All who were selected to attend were passionate about engineering research. They were eager and curious to connect and collaborate with a network of like-minded peers. They brought a diversity of perspectives to identify Tomorrow's Engineering Research Challenges. The workshops encouraged multidisciplinary thinking and accommodated focussed discussions that were supportive, inclusive and mutually respectful.

- **'Roundtable' meetings** – This series of virtual meetings brought together important groups of engineering stakeholders to bring dedicated perspectives of engineering challenges as well as views on the wider needs of the engineering community. This included Presidents and CEO's of the leading professional engineering institutions, industry CTOs, leaders of engineering EDI groups, early career researchers, PhD students and government chief scientific advisors – all of whom openly shared their opinions through discussions led by the co-chairs.

- **International perspectives** – Academics and experts from selected international organisations, including National Academies of Engineering, were canvassed to gain global views of engineering challenges. These written contributions aimed to complement the wider engagement.

What does this report say?

This report is a key output that draws together the key findings, themes and challenges from this suite of activities. It presents an objective account of the evidence gathered through the focussed, thorough, community engagement with the specific aim to inspire further dialogue in the research community and to inform future research strategy. Importantly, this report sets out some key recommendations for UKRI, other partners and the engineering community to set a clear trajectory for future action, which are supported by the evidence from the discussions.

This report is structured in a hierarchical way, from High-Level Priorities to Cross-Cutting Themes and to Technological Challenges, whilst recognising that each of the challenges cannot be considered in isolation. This important principle of integration has been recognised throughout the TERC engagement process and the writing of this report, where there has been an endeavour to align content from different engagement activities where they are synergistic. This has been indicated throughout the report and in some cases may also convey the links between engineering and other disciplines, including the social sciences, and consider the global landscape of engineering. Whilst the reference to these links is not comprehensive, the reader is also encouraged to identify further interconnection between the challenges.

The High-Level Priorities, Cross-Cutting Themes and Technological Challenges are presented sequentially in this report and illustrated in figure 1. Each set represents a convergence of viewpoints, where we have tried to preserve as much of the language and sentiment of the contributions as possible to convey the context, importance and emphasis of the discussions.

In the annexes, we have presented the important supporting evidence behind each of the priorities, themes and challenges. This evidence is grounded in the engagement activities. In Annex A, we provide a summary of each of the roundtable discussions to provide a context and focus shared by each of the diverse stakeholder groups. In Annex B we have reproduced the important and necessary granularity under each of the Technological Challenges, including antecedent research necessary to address each challenge and suggested enablers and barriers to overcome. In each challenge, we also cross-reference relevant viewpoints taken from the stakeholder roundtable meetings, where they add specific insight or value.

What is the intended outcome?

A realistic outcome from this piece of work is to encourage positive impact across the engineering discipline. However, success will only be achieved if there is strong connection and collaboration across the whole engineering ecosystem. Therefore, the recommendations from this report will need to be progressed by many stakeholders: EPSRC as the main funder of engineering research and skills; other UKRI partners and funders of UK research; the Royal Academy of Engineering; universities; professional engineering institutions and learned societies, industry, policy makers across government and the academic research community itself.

To resolve the challenges identified requires multiple agencies, institutions and disciplines working together in an inclusive way, to achieve impact and engineer a more sustainable, resilient, and productive future.

High Level Priorities

The priorities in this section draw together specific viewpoints from our community dialogue and represent overarching requirements to enable the research community to address Tomorrow's Engineering Research Challenges.

Promote inclusive engineering outcomes for all with more diverse input

Our dialogue with the community highlighted the importance of inclusive engineering. Inclusive engineering is the discipline of ensuring that engineering products and services are accessible and inclusive of all users, and are as free as possible from discrimination and bias. Classic examples of non-inclusive engineering are soap dispensers that do not work if you hand is black; camera software which does not recognise gender correctly and artificial intelligence algorithms which favour one race over another.
Our consultations underlined that the researcher community should be diverse and should operate in an open, inclusive and respectful way where contributions from every angle of thinking are valued. The definition of research projects and programmes and their outcomes should be similarly inclusive. Engineering solutions should work for everyone, from every social class, every background and wherever you are in the world. To create inclusive outputs it is necessary to ensure diverse and inclusive 'inputs', including a diverse and representative community, an equitable system where all participants can thrive, and a willingness to work with partners and collaborators representing multiple stakeholders. Research results should be available in an accessible and open format. To facilitate the adoption of inclusive input practices as widely as possible, a strongly supported idea suggested through our engagement was to provide incentives (or rewards) to encourage sector-wide change.

To greater ensure the outcomes of our engineering research are inclusive, the community noted that engineering research should be co-created with the end users and beneficiaries and designed to be fit-for-purpose. This should not only be done with a UK perspective, but it should consider the challenges that global populations face; ensuring those most affected have meaningful representation and a stake in the research. Engineering has an important role to play to reshape our current model of economic development beyond constant use of technology and depletion of resources. These sentiments were further developed in the health and wellbeing, responsible engineering and global engineering systems Technological Challenges.

The barriers facing under-represented groups are reasonably well-understood, but there is a need for accountability, transparency, fairness, and more education to challenge harmful stereotypes, as well as to challenge the effect of groupthink and the misconception that creating equitable systems means lowering the bar. The research community also highlighted the issues facing career progression for researchers in under-represented groups, where lack of visible role models, implicit biases in recruitment and training, and perceived lack of access to networks of experts are barriers. Inclusive practices eliminate bias and allow access into a larger pool of talent where opportunities such as mentoring and impromptu networking can provide benefit, particularly those with caring responsibilities. Diverse research teams inherently provide greater diversity of thought that ultimately enhances the outputs and impact achieved.

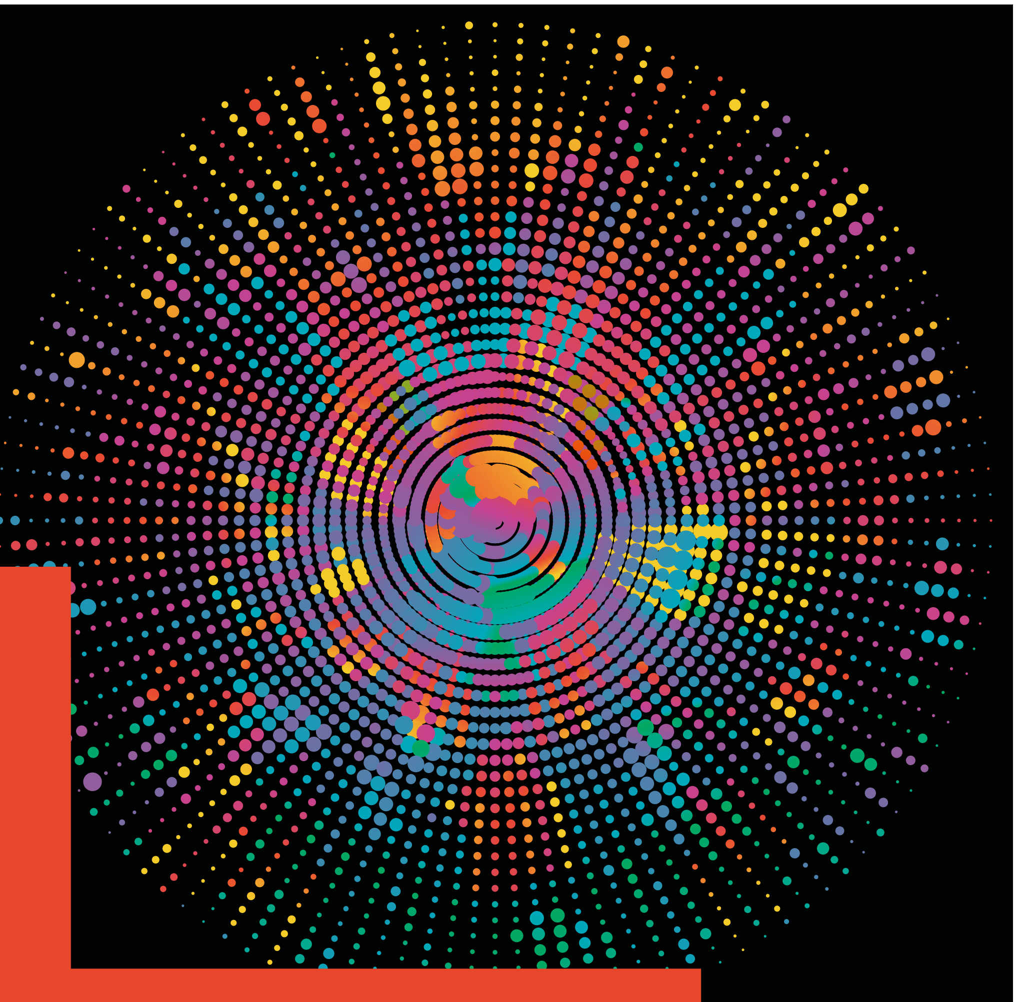
[1] www.inceng.org website produced as part of the Royal Academy of Engineering Visiting Professorship scheme

Strengthen mechanisms to facilitate and fund multidisciplinary and interdisciplinary research

Our consultations emphasised that in the years to come, engineering will be confronted by more complex, interconnected, diffuse and socially embedded issues. It is almost impossible to set up the problem in terms of optimalisation, as we have done in the past. We must ensure that challenges do not become too segmented, since they require integration and inclusive input from many disciplines.

There is a need for engineering research to serve a purpose and provide heterogenous solutions for heterogenous populations to deliver value across social, technological and environmental dimensions. This requires bringing disciplines together in a multidisciplinary way (involving multiple disciplines to solve a problem) or interdisciplinary approaches (combination and synthesis of knowledge). Many examples were drawn from our engagement, such as encouraging engineers to engage with social sciences and environmental science to influence engineering research thinking and doing this at an early stage to consider the social and environmental impact of novel solutions. There is a challenge to break down traditional siloes and work closely together with others to enable truly multidisciplinary research, which also includes the shared understanding and use of tools and methods from contributing disciplines.

The prominent message which emerged from our discussions was the need to standardise terminology, especially in emerging fields, to ensure research is reproducible and progress can be accelerated. Thus, there is a need to encourage better communications between disciplines to break down technical language barriers and to establish mechanisms to ensure multidisciplinary and interdisciplinary proposals are more competitive and successful. Funders and supporters of engineering research will need to embrace new mechanisms to accommodate this viewpoint.



Re-engineer the discipline of engineering

In some of our conversations with the community, the question was raised to whether engineering should continue to be defined as a distinct, bounded discipline.

Whilst fundamental, discovery-led science and engineering provides the foundations from which application-focussed research is built, there is a need to bring unique knowledge from scientific principles and mathematics to enable engineers to develop innovative solutions to transform the latest discoveries, enabling new technologies such as quantum technologies, engineering biology and artificial intelligence (AI). Our engagement revealed that there may be benefit in combining aspects of science with engineering or expanding engineering boundaries beyond traditional remits. Engineering is and should be an interdisciplinary ‘science’ and a method to rapidly transition science into application to create more innovation, profitable companies and valuable products. Herein is an opportunity for the UK and we should be positioning our young engineers to be entrepreneurial to enable this to ensure we are fit for the future, and not dwelling on short term considerations.

Furthermore, the big societal challenges of climate change, resource consumption, migration and economic disruption require agile approaches so that we can absorb shocks (economic, pandemic, environmental) in a manner that reduces the impact upon society. A key message that emerged was that Engineering can play a role here. There is an opportunity for engineers to be more agile and resilient; adapting to have a better understanding of global challenges to achieve real world impact. Engineers also need to understand that almost every one of these systems is socio-technological which has humans in the loop and so must work with human behaviour and idiosyncrasies. For example, throughout many of the Technological Challenges identified through this exercise, ideas were suggested to encourage a new breed of engineers to help support and enhance the social value of engineering solutions. Understanding and embedding of ethical principles and practices into future engineering solutions also plays a vital role here. There is a requirement for further training and skills in this domain to promote responsible and ethical leadership of new technologies and ethical decision making, particularly if engineering solutions are integrated with human users.

Our engagement has suggested that, as a nation, we should challenge the current state of engineering which reinforces a conventional or orthodox view of engineering practice towards one that is placed at the crossroads of ‘science of nature’ and ‘science of human’. Identification of challenges that relate to ‘Engineering in society and engineering for society’ will become most critical in the coming years and therefore, the practice of engineering will need to adapt and evolve to become more agile and resilient. There were further suggestions that engineering will need to be much more porous to arts and creative design models and there is a heightened need to develop engineers who are comfortable working across the boundaries. Future engineers will need to be skilled and able to dynamically develop research amidst rapidly evolving needs, societal and environmental, and to support this we will need to create a new and different professional culture.

Convene and connect with the professional engineering community to enhance impact

Collectively as a nation and globally, we will need to have the capacity to identify challenges beyond problem-solving and a solution-providing lens, while adding value by translating them into actionable engineering terms. This approach calls for interdisciplinary effort, collaboration, co-creation, and co-evolution, all based on mutual respect amongst stakeholders. Our engagement processes proved that bringing a diverse representation of expertise together around common questions can yield positive and potentially transformational results.

Networking between seemingly disparate groups can bring new insights and perspectives. The ability in discovering challenges outside of traditional engineers' fields of expertise is important and the process of engaging all stakeholders around potential challenges, facilitating discussing with them, exchanging ideas and working together would be essential to facilitate this shift.

As mentioned in several of the challenges, performing engineering solutions at scale is vital to achieve impact and deliver cost savings. Whilst accommodating regional and national priorities, many challenges identified throughout our engagement are unlikely to be just UK-centric and ought to be considered globally. Many participants highlighted the importance of maintaining and expanding national and global networks; keeping a global view in research. Therefore, the importance of international collaboration to achieve optimal scale, adoption and resilience to solve more global challenges effectively needs more attention. For longer term challenges this means 'international scale' research and standards.

Ultimately, many of the challenges can be tackled simply with time, effort, will (political) and money. These all represent barriers to collaboration, but removal of barriers in science might unlock, and support, true global collaboration and partnerships. Encourage diverse, agile and impactful skills

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Encourage diverse, agile and impactful skills

Throughout our community engagement, there was a strong emphasis on the important need for skilled people if we are to solve Tomorrow's Engineering Research Challenges.

The acquisition of new skills or reskilling the existing workforce should be a priority for the engineering community, in conjunction with better guidance and funded training for young people so that they are better prepared and equipped for the roles that employers need to fill. Skills are required at all levels from apprentices upwards, alongside an environment conducive to advancement and retention.

To future-proof our next generation of engineers we need to revisit the current engineering education programs, mostly discipline-based and solution-oriented, by integrating further economic, environmental, human and societal dimensions. Specifically, there is a requirement to identify the engineering skills needed, ensuring sustainable provision and supply through education and training. We need to ensure that curricula meet future needs, particularly in maths, technology, sciences, philosophy and ethics.

Our future engineering graduates should be well versed in data science, systems thinking and digital engineering and there is also a requirement for responsible and ethical leadership of new technologies, to appreciate the benefits and limitations of technologies like AI and machine learning. There is also clear demand for digital and green skills, ethical decision-making, and effective public engagement so that future engineers have an appreciation of where engineering lies in terms of sustainable development and responsible production. The content of engineering degrees is accredited via the Engineering Council and the professional engineering institutions, who already place emphasis on these topics.

Opportunities for multidisciplinary and cross-disciplinary training are valuable (particularly at graduate level through the Centre for Doctoral Training model), as it gives a more holistic understanding of engineering, but further flexibility could enhance this (e.g. allowing students to choose some of the modules offered through their institutions in different disciplines). There was strong encouragement from many participants to continue to support mobility between academia and industry to further open the pathway of pursuing a PhD to people from industry who are interested in doing research, as well as to offer PhD students the skills, networks and insight to be able to transition to industry after their PhD if they wish to take that route. Of course, a more competitive stipend for PhD students would increase the chances of attracting interest from more people, including from industry. As a nation, we really need to value our PhD students, especially in such a competitive marketplace.

Fellowships offer an opportunity to provide freedom for our researchers of the future, and so qualities of agility and ability to generate impact need to be built into that community. The community highlighted that we also have to be careful not to neglect the group of mid-career engineers who are competent engineers but with outdated schooling. We need to foster a climate of agility where we are able to retrain people in areas at risk of loss of skills (such as oil and gas, and foundation industries). However, it was recognised that graduates in 10 – 15 years' time will be using technologies and processes that have not been invented yet, so instilling the capacity for life-long learning is most important. It is essential to ensure that Continuing Professional Development (CPD) at all levels and career stages is used to bring in new technologies, and the outcomes of future research, to the workforce.

Inspire the next generation

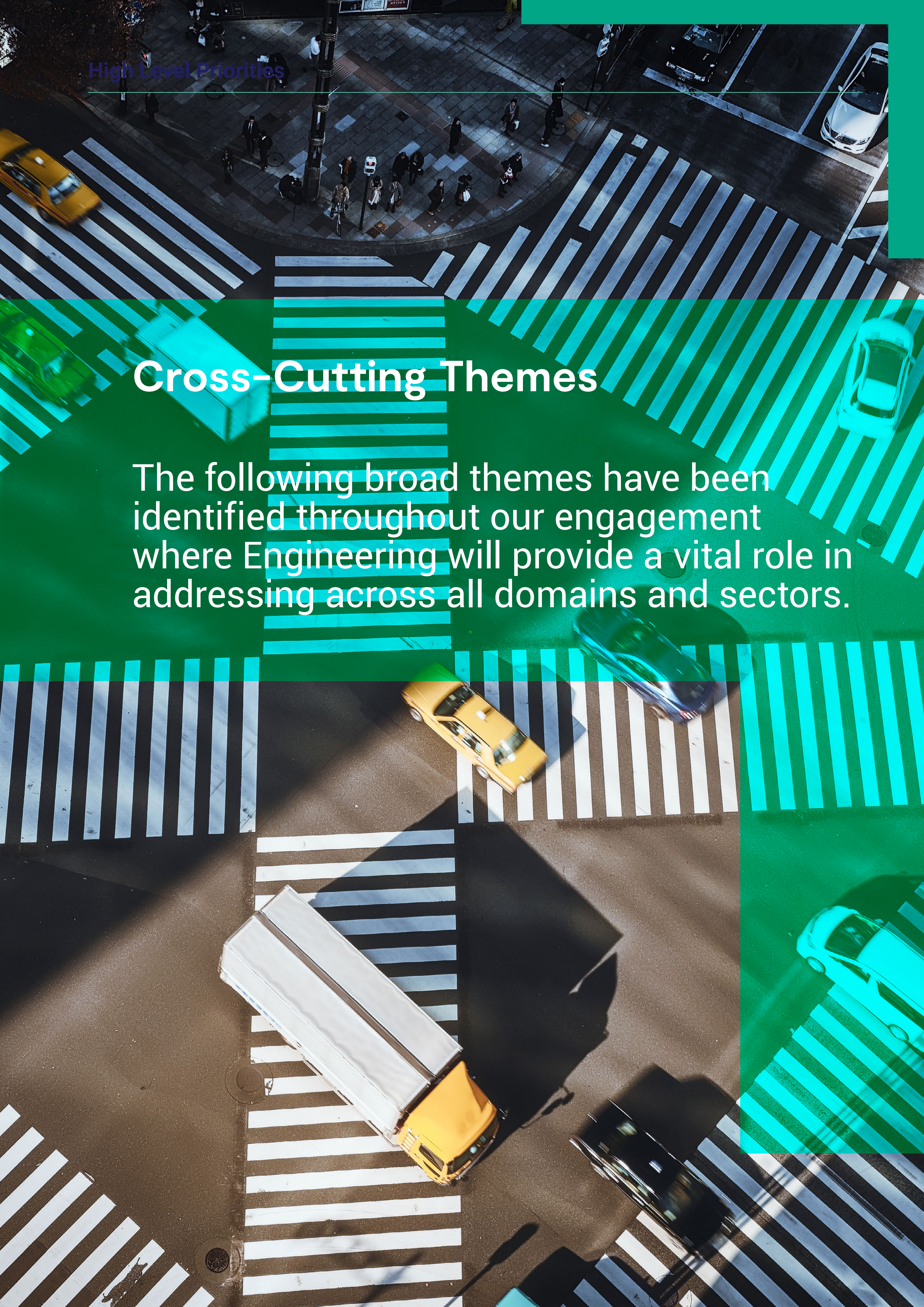
Our stakeholders were clear that we cannot examine Tomorrow's Engineering Research Challenges if we don't cultivate the talent and elevate the importance of engineering today.

An overwhelming message from our engagement was the need to inspire young people from all backgrounds into engineering. There is the perception that many groups hold outdated preconceptions of what engineering is and that those people from disadvantaged backgrounds often have the least knowledge of engineering. It is important to showcase the opportunity that equality, diversity and inclusion creates for the engineering sector as there are many excellent people who simply do not see engineering as a potential career path which can be detrimental to us all. Those we engaged with felt that young people often choose careers based on making a positive difference to society and improving our environment. Engineering provides an anchor profession to enable this and has the platform to inspire wider society on the contribution it can make to improve people's lives.

The importance of outreach to younger ages was raised and the requirement to plant the seeds of enthusiasm of science, engineering and research from an early age. There is currently a plethora of activities to get young people interested in engineering.

There is a view that engineering should be better represented in the compulsory school curriculum and its delivery could be more personalised so that it fits better with the needs of pupils with different characteristics and abilities.

For the next generation of engineers there not only needs to be academic course provision, but also take up (both of staff to teach and the students to take the courses). Here, there is a role for funders, professional bodies, universities and industry to support researchers and the existing workforce to inspire young people and look at how engineering is represented in the compulsory curriculum and wider society. This kind of outreach is also undertaken by PhD students and it was noted that it would be beneficial if PhD students were further encouraged and supported to pursue those activities. Encouraging more people to pursue a PhD in engineering was repeatedly highlighted during our conversations, alongside the importance of raising awareness of the benefits of an engineering degree. It was further highlighted that engineering research is a very creative route and research careers are stimulating, diverse and flexible, and thus offering more opportunities and benefits for a wide variety of people. Creating welcoming environments that make people feel safe and paying attention to mental health were also noted as desirable requirements to attract future workforces into STEM careers.



Cross-Cutting Themes

The following broad themes have been identified throughout our engagement where Engineering will provide a vital role in addressing across all domains and sectors.

Achieving net zero and sustainability

Climate change is a major challenge that affects all aspects of our lives. Our engagement has highlighted that there is a prominent role for engineering in achieving net zero and sustainability. This was conveyed as an engineering challenge that needs to be undertaken at scale, whether it is developing green and renewable technology, the responsible and efficient use of materials or promoting healthy perceptions of a green economy.

To ensure success, the community identified a strong emphasis on the greater adoption of systems thinking and life cycle analysis, including assessment of accurate, reliable carbon footprints for different systems and developing technologies with lower material content. Decarbonisation of industries was revealed as a key area of focus through our engagement. Many engineering opportunities exist to reduce energy consumption and transition to alternatives to oil and gas, especially in energy intensive industries. In the context of the foundation industries (steel, paper, ceramics, glass etc.) reduction of energy and gas, greener technologies, use of hydrogen and putting in place new decarbonisation technologies for 2030 and beyond are fundamental, particularly if all these industries have an interest in future competitiveness. However, measures will need to be adopted without compromising product quality, standards or yields.

The hydrogen economy was highlighted as becoming increasingly important. The community stated a need for stronger research focus on its application, particularly if the gas network can be repurposed with hydrogen.[2] There also needs to be an active comparison of green, blue and grey hydrogen in terms of ease of production, costs, green credentials and technologies to transport hydrogen efficiently and safely.

Battery storage technology is also developing rapidly, and there is a challenge for the research community to continue to help drive this forward to help inform the standards and guidance. Improved battery technologies, including greater capacity and lifetime are important, as well as recycling and separation of the various materials. The community also identified that as a nation, we will need to have reliable and sufficient grid-scale energy storage, but this is a huge challenge in terms of materials use, costs and practicalities.

The collective view was that there is a strong role for the research community in all of these aspects. This will require the ability to develop advanced methods and technologies (such as digital twins to optimise resources through testing) and techniques to identify and map UK resources, including assessment the ease, cost and energy demand of extraction and incorporation and use of compostable and biologically-derived materials. Our future engineers can advance sustainable practices across sectors (from manufacturing to agriculture), increase the efficiency of carbon capture and storage technologies and develop novel and inclusive solutions (particularly nature-based or naturally accepted solutions) to mitigate further climate change and adaptation. The government drive for net zero emissions and UKRI's focus on net zero is just the foundation for a sustainable inclusive society.

In relation to this, a standout challenge is enhancing the public acceptance of technologies that will facilitate net zero. Engineers and the wider community must be able to consider the social, environmental impact of solutions and work to help develop public trust if we need industry to adopt alternative, renewable and new energy technologies and ensure that we do not worsen things environmentally or degrade our biodiversity by adopting such technologies.

[2] The IET's Energy Policy Panel had completed some initial thought leadership in repurposing the gas network to hydrogen and highlighted some of the engineering challenges and risks.

Faster digital design

Design was raised as a key challenge by the community, since it casts the biggest shadow for carbon net zero and cost, and excellent design processes are necessary to have control of supply chains. Supply chains are complex interconnected systems, with lots of inputs and beneficiaries alongside a plethora of new materials and technologies. However, what is missing is an accelerated way to test and trust the data available and this creates a bottleneck for innovation. Therefore, finding rapid ways to test, assure and validate was identified to be an important challenge for academic research.

In an increasingly digital engineering environment, new technologies and computational power are likely to play a major role in the design process. Digital twins, AI, robotics, automation, the internet of things, machine learning, cloud edge and exascale computing can all be adopted to accelerate, enhance and automate the design process across whole areas of engineering practice, providing that these are used ethically and we remain aware of cyber vulnerabilities. Cyber-physical interfaces can also rapidly transform many areas of engineering and manufacturing, providing its application can be understood.

Our discussions highlighted that advances in digitalisation and design can impact key sectors, providing solutions are co-created and co-designed with end users and communities. For example;

- In aerospace much work needs to be done into the fast design, optimisation and certification of novel technologies and configurations in a safe and efficient manner and to integrate new materials (including functional materials and structures) that can adapt the aircraft shape or be used as batteries.
- In transport, the sector is becoming increasingly digital and adaptable solutions need to be designed to meet the needs of end users and ensure these are seamlessly merged with the existing civil infrastructure.
- In construction, there are opportunities to use AI to undertake mundane design of typical infrastructure, freeing up engineers to be more creative and demanding in their designs and spend more time to consider and embed safety aspects. Future building designs will have to anticipate climate-related changes as well as consider new shifts from sustainable design to restorative or regenerative design.

The community noted the need for training to understand interdependencies between design, performance, functionality and impact on people, and the need to consider long term consequences during the developing process and not just after technology has already been developed.

Finally, engineers should make more use of people-centric design and adopt more exploratory, creative and goal-directed design, which represents an opportunity to bring in the arts community to imagine, envision and design a different future.

Greater access and use of data

Many of our stakeholder groups noted that for decades, we have been creating huge quantities of data, with increasing use of sensors, internet of things and computing systems generating more. New engineering solutions rely on and evolve due to increased data sets, but there is a widely agreed need to close the gaps in our ability to generate data against our ability to intelligently process, and to ethically use, data. This applies right across engineered systems in numerous sectors, including transport, healthcare and space.

Harnessing big data (or even sparse engineering data) is the key to move on from legacy assets to more digital environments (including adoption of Industry 4.0 and digital twins) and there is an opportunity to understand and utilise the power and limitations of new tools and techniques (e.g. exascale computing, quantum computing, AI and machine learning). This will help us focus on understanding the wealth of data we already have and learn from it.

Whilst the clear message from the community was that greater access to and use of data can facilitate our journey to a digital future, we need skilled engineers who can understand and navigate the wealth of data, use data effectively and to adopt and optimise the use of AI, machine learning and other data acquisition tools.

Finally, access to and proving the value of qualitative and quantitative data and information management was highlighted as crucial for effective research and to encourage a meaningful transition in working practices across the engineering sector. Better exchanges of data across public, private as well as temporal and geographic boundaries would foster innovation.

Increasing human resilience

Human resilience in the face of unprecedented challenges, such as climate change and global health crises, was highlighted as one the main challenges for the next 10-15 years by many of our stakeholder groups.

Engineers have a strong role to play in the mitigation of the effects of climate change, but rapidly changing climates could easily overwhelm engineers' ability to fully protect all communities from flooding, drought, or wildfires. Engineering solutions can ensure resilience to change at a local level, but we need to take a global perspective to ensure we can live sustainably as a society. Even circular technologies developed for the space environment can be translated back to terrestrial application to enhance quality of life on Earth.

The engineering sector has an important role to play in providing the tools, skills and means for humans to cope with these challenges be it through technologies for green energy, decarbonisation, carbon sequestration or public health engineering. These include skills in risk analysis to consider acute and chronic risks to people and the planet, including hazards traditionally not in the engineering domain (e.g. climate impacts, social inequality, loss of biodiversity).

The role of engineering in infectious disease control has been acutely exposed through the recent Covid pandemic and continuing studies on air and water quality and their control will be essential to tackle future disease. Developments in the re-manufacture and re-use of medical equipment will also help to ensure sustainable healthcare solutions and engineering healthier environments will promote our wellbeing, ensure healthy aging, and enhance quality of life for all.

Understanding complex systems

Many of the challenges identified through this exercise were characterised as 'systems problems' as they are often complex, multi-faceted challenges, involving hundreds of parameters and different sub-components, each with unique behaviours.

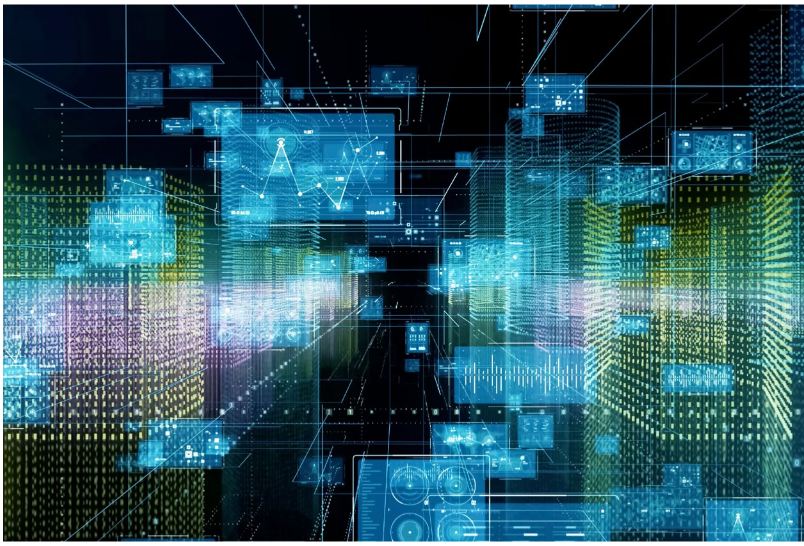
Some international members of the community noted that some of the more fundamental and expansive challenges for the future will be in the realm of complex adaptive systems, as in energy transitions to address climate change, healthcare, and transport; all have asynchronous impacts on communities and industry. Any responsible measure, be it efficient manufacturing or effective waste management, will require and necessarily build on a sound understanding and adaptation of systems engineering practices. The continuing need to learn from natural processes to guide the evolution of systems design, operations, and maintenance will be a fruitful and challenging arena for research.

The community also emphasised that there is a growing need to make 'systems of systems' work. Systems of Systems involve the integration of multiple individual complex systems. These systems often have human considerations embedded, which adds an additional layer of complexity into any solution. We found through our engagement that application of these types of system often extends beyond traditional engineering, where there is a challenge to understand the bigger picture and to co-design systems that consider the impact on people. This could help us overcome a tendency to look for 'provable systems' that forces us into hierarchical and resilient systems architectures which may not be the most efficient nor necessarily the most effective.

A system of systems approach can include aspects of integrity, ethics, safety and understanding consequences informed by data-centric engineering approaches. The approach inevitably needs to draw on stakeholders, both within and external to the engineering community such as sociologists, economists and computer scientists.

Tools such as digital twins can enable the real-time monitoring of these complex systems using innovative data from sensors in a virtual environment. However, the view is that this will need to be done at full scale, since it is challenging to replicate the conditions of a system in a laboratory. Digital twins also offer an opportunity where control systems or use of control aspects can help embed systems into a range of environments.

Of course, people need to be upskilled to provide systems perspectives, but a key barrier for systems engineering approaches is hyper-specialisation, notably in climate and health systems. While some degree of specialisation is helpful, the inability to systematise concepts and insights from research and development will be challenging and requires our engineering graduates (and researchers) to be well versed in traditional systems-thinking and to appreciate the benefits and limitations of technologies like AI, digital twins and machine learning.



Harnessing disruptive, emerging technologies

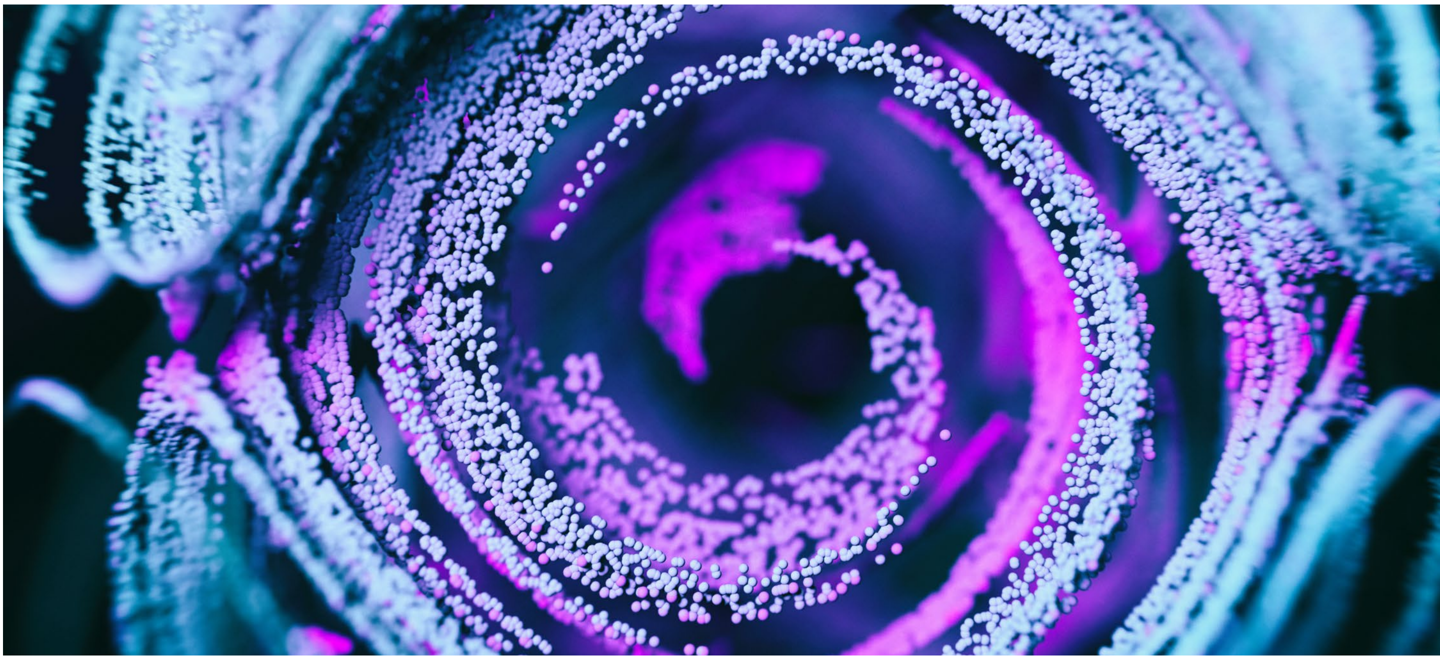
Quantum technology, neuromorphic computing and engineering biology are just some examples of emerging technologies that have the potential to enable us to meet Tomorrow's Engineering Research Challenges and to revolutionise the world as we know it.

Our engagement emphasised that there are significant challenges in developing the engineering science pipeline to translate these technologies into real-world benefits, specifically for quantum technologies. If we succeed in progressing quantum science into engineering, then manufacturing into transformative applications, we will have the capability to run powerful simulations, ensure secure communications and navigation, solve complex and multi-scale problems more rapidly and design and optimise machines far faster than today.

For the UK there is an opportunity to upskill our engineers sufficiently to harness these technologies to meet our aspirations, specifically to advance the manufacturability of these technologies and establish a trustworthy landscape for their democratic use and adoption. Importantly, there is the need to involve regulators in early-stage development of new technologies, so intelligent regulatory frameworks can be put in place to support our ability to deploy these technologies faster and more effectively.

The global dimension was also raised during our discussions as an important factor since it will have significant impact on the way new technology is developed and implemented in the UK. The UK should look to the global organisations that set standards for new technologies, as part of the analysis of global trends, and should consider how the UK engineering community can develop and influence these standards to allow the UK to gain greater competitive advantage especially when looking to export new technologies.

Our community recognised an opportunity for trained engineers to enhance public trust in new technologies, which requires outreach and communication to the public in an open, inclusive way. Also, the ability for engineers to specialise in identifying potential technologies that very rapidly move from one to another industrial sector and enable innovation were seen as attractive, as developing and patenting these would have immense economic payback.



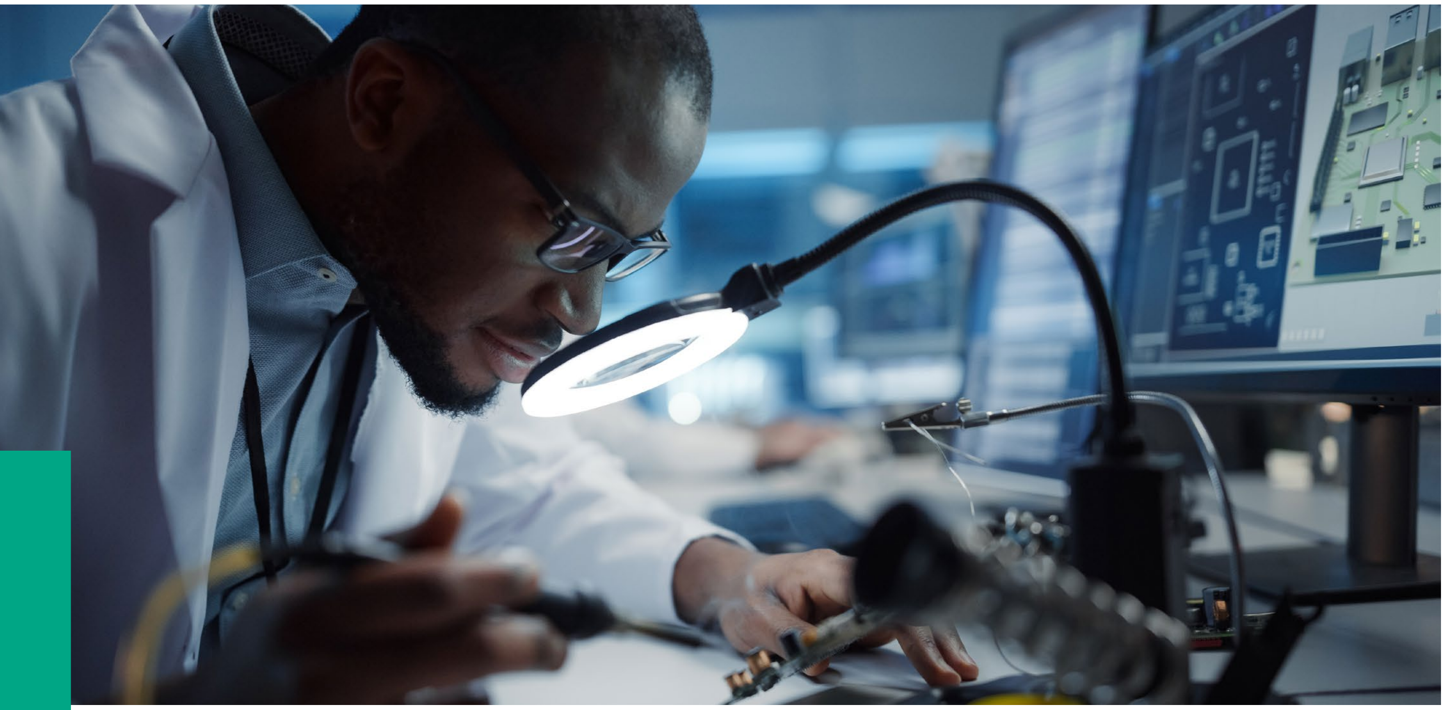
Underpinning tools and techniques

Throughout our engagement, most of our attention was drawn towards application or sector driven challenges, but the important role that engineering plays in developing the underpinning tools and techniques to enable future solutions was not neglected.

There was support for encouraging engineering scientists to research, develop, and design new materials, devices and sensors that can aid the process of translation into a diverse range of applications. New analysis methods, tools and techniques can provide a greater range of methods that can be tailored to specific problems. Numerous examples were highlighted during our discussions:

- Tools to aid material and process selection and better compare materials can benefit their application;
- Analysis techniques, such as non-destructive evaluation, which can evaluate the properties of a material, component or system without causing damage, could enhance manufacturing practices and enable the move towards increased digitalisation and automation of the engineering and manufacturing sector (Industry 4.0).
- Design tools and testing paradigms to enable the understanding of how living biotechnologies and materials may change beyond their expected function in applications.

The freedom to allow engineering scientists to develop novel underpinning tools and techniques was viewed as critical, as many of the tools currently available are from commercial organisations which generates a risk that the data and analysis is skewed to suit a certain range of products or services. These underpinning technologies will provide the essential tools to greater enable the wider engineering community to tackle the grand challenges.



Technological Challenges

This section frames the most ambitious technological challenges for the next 10-15 years, defined at the academic workshops, where application of engineering research will be vital to provide solutions. The important and necessary granularity under each of the Technological Challenges, including antecedent research necessary to address each challenge and suggested enablers and barriers to overcome are provided in Annex B.

Space

Ensure **space research** is sustainable, and design and develop technologies that will be used to explore and sustain life in space and on Earth.

Space plays a critical role in our daily lives. Satellites and space activities deliver navigation, communications, weather forecasting, power grid monitoring, financial transactions, and better public services. Space is unique in its capacity to grow our economy, transform our society and inspire us to greater heights of human progress. In this context, research in the space environment has great potential to inform the preservation of life back on Earth.

From an engineering perspective, space can be considered an extreme circular environment that offers opportunities to design for life with limited resources, such as for sustainable energy generation and recycling and reuse of materials and technologies. The extreme conditions in space also provide a unique testbed for solving multi-scale problems from harnessing big data to inform the design of manufacturing processes to the provision of basic human needs. Engineering can help to realise the terrestrial benefits from space research.

To achieve this challenge, the community identified the following questions to be addressed:

Q1: How can we harvest existing space-based resources (reusing and recycling where possible) to provide for humans to live in space?

Q2: How can we use the extreme conditions in space as test beds for life here on Earth?

Q3: How could space be used to help meet basic human needs, such as food, and provide a method for manufacturing of specialist items?

Transportation Systems

Develop sustainable, integrated, and equitable **transportation systems**

Many of history's greatest engineering endeavours have manifest in the form of transport. The rapid advancement of vehicle technologies and the construction of interconnected infrastructure has eased our ability to travel by road, rail, sea and air. But times are changing.

In the future we need to ensure that transport systems meet the needs of individuals and societies as well as make them flexible to adapt to change. And we are increasingly seeing aspects of the transport system becoming more digital. The role of engineering is critical to support this revolution and can help us to ensure equitable and accessible transport systems, develop clean energy and zero emission technologies and to encourage us look more holistically towards sustainable, affordable, multi-modal integrated transport of goods, services and people in urban, sub-urban, rural and remote contexts. Ultimately an integrated systems approach is necessary where people and communities are involved in the design and development of transport solutions that incorporate all modes, including walking and cycling.

To achieve this challenge, the community identified the following questions to be addressed:

Q1: How will we store, convert and distribute truly sustainable energy for transport and develop propulsive technologies to use that energy efficiently?

Q2: How do we develop transport infrastructure and the transportation system to deliver integrated connectivity?

Q3: How might engineers contribute to developing equitable and accessible transport systems?

Materials

Accelerate environmentally sustainable and socially responsible creation and utilisation of **materials**

Materials have defined the early stages of human history - stone, bronze, iron - and have continued to play a vital part in the development of the modern world. Engineering has harnessed these materials and created the structures, machines and technologies that today pervade our daily lives. However, sources of useful materials are not limitless and there is an urgent drive to phase out fossil-derived materials. Engineering can provide the tools and approaches to ensure our future use of materials is more sustainable.

To be environmentally sustainable we need to be socially conscious of the economics and ethics of material choices and ensure that we are considering low impact sourcing, embedding end-of-life approaches from the outset and confidently favouring sustainable alternatives. This includes the use of materials in advanced design and manufacturing. By employing sustainable methods of engineering materials, we can invoke a new materials 'age' to enable humans and the environment to flourish.

To achieve this challenge, the community identified the following questions to be addressed:

Q1: How should we enable an economically viable transition to responsible, sustainable, renewable, circular materials and technologies?

Q2: How should we replace 'virgin' fossil and rare/ toxic/ mined materials with responsible, sustainable, renewable, circular materials?

Q3: How can we disrupt pathway dependencies in materials design and manufacturing to meet future market demand for radically more sustainable products?

Health and Wellbeing

Improve **whole-life health and wellbeing** by developing sustainable, inclusive, and resilient healthcare systems and technologies

Engineering provides a vital contribution to ensuring health and wellbeing for all by providing a bridge between the sciences to develop novel applications, medical technologies and innovative treatments. In the future, engineering will be important in the health sector to improve healthcare in ways that are faster, more efficient and more equitable, through technologies such as advanced health informatics, innovations for personalised medicine and systems engineering principles. This can add significant value to individual patient care by enabling more accurate detection, diagnosis, treatment and prognosis and to the wider healthcare system through better modelling, use of smart data-management techniques, and engineered solutions for resilient and sustainable practices.

New engineering tools and medical devices can inform and develop predictive systems and the use of technology to educate and inform, so that individuals can take ownership of their own healthcare needs and accommodate personalised solutions to encourage wellbeing to improve quality of life.

To achieve this challenge, the community identified the following questions to be addressed:

Q1: How should we provide an inclusive approach for the development of healthcare solutions throughout our lives?

Q2: How might we re-engineer complex healthcare systems for resilience and sustainability?

Q3: How might we develop novel solutions for inclusive, lifelong wellbeing?

Robotics and AI

Co-design and embed **robotics and AI** into engineering while ensuring ethical use with transparent and equitable decision making.

Robotics and artificial intelligence represent emerging technologies that can potentially revolutionise our lives. Both promise to have profound impacts on all areas of the economy with the potential to address national and global challenges. However, there are many engineering research challenges that need to be addressed to realise the benefits of these technologies. Robotics is a multidisciplinary challenge which is in much need of engineering and integrated approaches to develop new solutions and systems, whereas the challenge for AI is to be based on, and embed, physical understanding to underpin decision-making to accommodate the revolution of its use into robotics. There is a need to embed these technologies into engineering systems in an ethical and equitable way for them to be useful, accessible and adopted by, and for, human users. Thus, inclusive engineering is of huge importance in this regime. The impact will be to improve sustainability and resilience, and enrich many aspects of our lives.

To achieve this challenge, the community identified the following questions to be addressed:

Q1: How can we certify algorithms and systems to make robotics and AI autonomous decision-making processes transparent?

Q2: How should we characterise the influence of robotics and AI on human decision making and behaviour, particularly where this relates to ethical and equitable use?

Q3: How should we ensure robotics and AI are directed to address challenges related to our quality of life, such as the sustainability of resources and the development of resilience.

Responsible Engineering

Foster **socially and environmentally responsible approaches to engineering** guided by our understanding of human behaviours and needs

Engineers have traditionally been perceived as those who design, build, or maintain engines, machines, or structures. Similarly, Engineering has been seen as the practice of realising novel solutions to today's problems. Whilst many engineers already consider numerous perspectives of the 'user', the future role of engineers needs to shift to become more inclusive and socially-responsible and focus on intelligent solutions that exist in harmony with our society and our environment. There is an opportunity for engineers to redress the balance to one of leading and developing research that allows them to champion inclusive engineering and better engage with society and policy makers. Furthermore, engineering as a discipline will need to shift to adopt multi-, inter- and trans-disciplinary approaches. This will benefit sustainable, resilient and liveable systems, such as enabling intelligent and ethical use of data to design processes, practices and techniques and determining how these systems interrelate and interact with each other and natural systems.

To achieve this challenge, the community identified the following questions to be addressed:

Q1. How can engineering account for, integrate and continually influence the social, economic and policy factors required to achieve sustainable, resilient and liveable systems?

Q2: How can we model, understand, and integrate data from increasingly complex and interconnected systems to help shape our solutions?

Q3: How can we develop new engineering science approaches that consistently produce solutions which consider costs and benefits at a society level instead of at a technology level alone?

Nature-Based Engineering

Unlock the full potential of **nature-based engineering**

Nature inspires engineering solutions and provides tools for their implementation. Engineered bacterial populations have long cleaned our wastewater; marine animals inspired the production of 'sharkskin' swimsuits; synthetically engineered microbes are now producing pharmaceuticals; natural fibres are the basis for newly marketed insulation products and ecosystem restoration is proposed for reducing flooding due to climate change.

There is much more engineers can do to use natural processes in the design and implementation of future engineering systems and technologies. Natural processes, and the ability for biology to replicate and grow, can be used to produce or modify materials. Individual organisms and/or ecosystems can be engineered to provide specific functions. The natural evolution of organisms, which acts to optimise specific functions within their environment, can inform engineering design. By breaking down the boundaries between disciplines, Engineers can advance bio-based and bio-inspired solutions that play to the strengths and unique capabilities of nature, that have evolved over millennia.

To achieve this challenge, the community identified the following questions to be addressed:

Q1: How should we generate data applicable to a range of specific contexts and use it at the various stages in the design and application of nature-inspired or nature-derived technologies?

Q2: How might we accelerate the lifecycles of natural materials and systems to prioritise and accelerate development and adoption?

Q3: How might we use biology and nature to move beyond the current materials paradigm and harness these in engineering applications?

Global Engineering Solutions

Deliver adaptable **global engineering solutions** that are compatible with our understanding of the planet's ecosystem

Engineering has shaped our planet and its innovations have enabled better quality of life, connection and understanding for its inhabitants. Since the Industrial Revolution, the use of engineering by the human population has however had a negative impact on our planet, depleting resources, affecting our climate and degrading resilience. New research should take account of the effect of the engineering solutions on the planet in both the present and the future. Engineers and researchers in engineering should work in collaboration with other professionals, researchers, experts and communities to establish well-informed, multidisciplinary and circular approaches to achieve responsible and resilient solutions for all. This will enable resilient engineering solutions at a global scale for sustainable and equitable use of our limited resources, practices to repair past damages, and methods to build efficient systems that work in harmony with the eco-system of our planet.

To achieve this challenge, the community identified the following questions to be addressed:

Q1: How can we develop resilient systems approaches to ensure resources (e.g. food, water and energy supply) are sustainable and equitable for all?

Q2: How should we circularise production, storage, and use of resources and energy to ensure end-to-end reusability and recycling?

Q3: How might engineering contribute to reducing and repairing the impact - both past and future - of human activities on the natural environment?

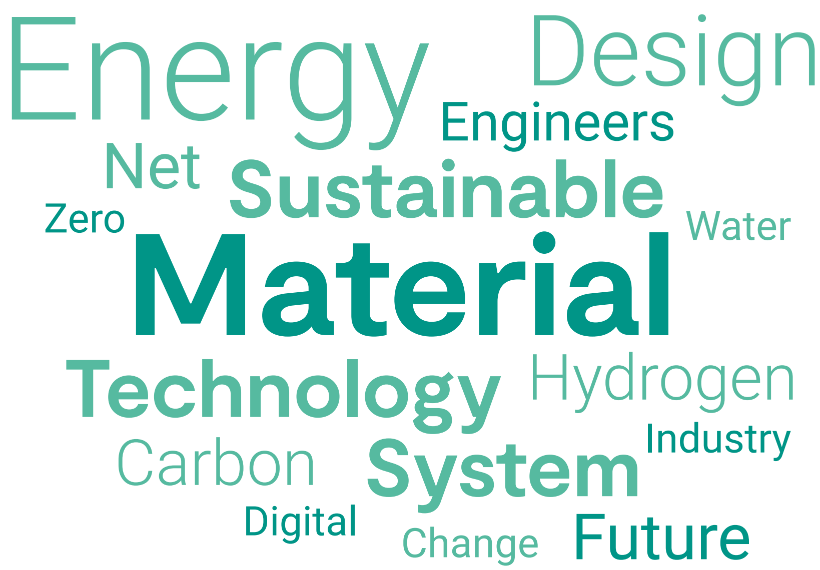
Annex A:
Stakeholder Perspectives

This annex provides summaries of the roundtable discussions held between October 2021 and April 2022, along with contributions from international representatives. This information represents important supporting evidence for the High-Level Priorities, Cross-Cutting Themes and Technological Challenges drawn out from the TERC engagement.

Professional Engineering Institutions and The Royal Academy of Engineering

Professional engineering institutions represent a vast network of knowledge and expertise across the UK. They have the capability to bring together academia and industry, provide mechanisms to continually upskill and reskill the Engineers, help to embrace interdisciplinary working and diversify the pool of talent.

There is a challenge in bridging the gap between practitioners' needs in terms of research outputs and the direction of travel of academic and other research funding, so it is important to the professional engineering institutions and related bodies that future engineering research addresses the issues they face in their day-to-day work. Feeding into activities such as Tomorrow's Engineering Research Challenges helps to bridge this gap.



Representatives from the Royal Academy of Engineering and some of the major Professional Engineering Institutions were brought together to share their thoughts on key questions aligned with Tomorrow's Engineering Research Challenges. Their answers revealed a number of interconnected themes and overarching needs, driven by the biggest challenge of our time, climate change. Sustainability, materials, energy and decarbonisation, systems, data/digitalisation, transport and skills were key areas highlighted in their responses to the questions:

1. **Looking forward over the next 10-15 years, thinking about members and institutions, what are the areas of impact you aim to be focussing in? What is your institution focussing on to create impact, what are your members going to be working on and to achieve what outcomes?**

Mitigating the effects of climate change emerged as a key target for engineers. However, as evidence suggests change is to some extent inevitable, a global systems approach is required to protect communities. The UK government pledge for Net Zero Emissions is just the start of what is needed for a sustainable and inclusive society.

Many challenges related to materials were identified. In particular, the social and environmental impact of critical raw materials including rare earth metals, which can potentially become scarce, needs attention. As usage of electric batteries increases it is important to produce batteries and motors with lower material requirements and overall environmental footprint, as well as to map and assess the ease of extraction of UK resources. Stakeholders at this roundtable emphasised the need to advance national processing capability to reduce reliance of the UK value chains on overseas supply. To ensure resource efficiency and advance a circular economy, a holistic approach of methods and tools of material and process comparison and selection needs to be developed, as currently commercially available tools carry the risk of being developed to suit certain products or services. We also need reliable life cycle and carbon footprint analyses, as well as a culture that fosters reducing, reusing and recycling. For the latter, recycling capabilities and public awareness need to be raised even further in order to increase the amount of material retrieved and the processing capacity in the UK, without requiring additional transportation. Packaging is one example with many opportunities to consider these aspects, which highlights the importance of having a sufficient supply of packaging technologists in the workforce.

The transition to clean energy and reduction of energy consumption, particularly for energy intensive industries, and without compromising product standards and yield are amongst the greatest challenges for engineers. To that end, the hydrogen economy is considered increasingly important, but comes with many open challenges related to applications, production and safe and efficient transport; for example, can the existing gas network be repurposed for hydrogen?[1] Other energy sources such as the next generation of nuclear technologies, which are considered important in the transition to a low carbon technology, present areas where engineers can achieve impact, such as old plant decommissioning, immobilisation and management, storage and transportation of hazardous nuclear waste, materials technologies needed for containment, storage and recycling, Small Modulator Reactors (SMRs) and Advanced Modulator Reactors (AMRs). The engineering research community also needs to keep driving forward the improvement of battery storage technologies in terms of capacity, lifetime and circularity of materials, and help inform relevant standards and guidance. Achieving decarbonisation will also require efficient carbon capture technologies, including challenges in improving transportation mechanisms and systems to reduce losses and ensure sites are clustered around locations that are close to end users.

Sustainable and resilient infrastructure was highlighted by the stakeholders in this roundtable. This was seen as a critical challenge, which will require systems thinking, complex systems and life cycle analysis. Going forward, decarbonisation targets should be at the heart of the way infrastructure contracts are structured and awarded. Future building designs will have to anticipate climate-related changes as well as consider new technologies, cybersecurity and economic and social priorities whilst being conscious of 'just building more'. Regarding the water infrastructure, more effort will be needed to allow the water sector to achieve net-zero operational carbon by 2030. In addition, air quality will be just as essential for health as water quality, including infectious disease control.

Transport is a sector undergoing significant change whilst at the same time facing urgent sustainability challenges. Future transport relies on clean energy and technologies (hydrogen, sustainable fuels[2], batteries). Hydrogen offers a solution mainly for "big" transport (planes, trains , trucks), but will be an in-demand resource and energy intensive to manufacture, bringing challenges particularly around sector usage prioritisation. However, achieving net–zero aviation is much more than just changing the fuel. Much effort should be focussed on achieving more efficient aircraft designs (e.g. better aerodynamics), sustainable manufacturing, optimised-efficient air traffic management and ground operations and reduction of other emissions in addition to carbon. In the exciting area of Urban Air Mobility (UAM) there are challenges related to the issues of noise and reliability, which require much further research and technological development. For autonomous vehicles in general, there are many novel applications that can be developed using sensing devices on an Urban Air Vehicle (UAV) platform, which will require advanced sensing technology from the physics and chemistry communities. Transport has struggled with digitisation, especially sectors such as railway and shipping, and we need core research capability to understand the challenges and propose standards and solutions. Digital technologies can also play a major role in fast design, optimisation and certification of novel technologies and configurations, for example, new functional materials and structures that can adapt the shape of an aircraft.

[1] The IET's Energy Policy Panel completed some initial thought leadership in repurposing the gas network to hydrogen and highlighted some of the engineering challenges and risks.

[2] The IMechE have produced three reports on transport this year, all of which touch upon sustainable alternative fuels: https://www.imeche.org/policy-and-press

Data and digital technologies, particularly information management, were identified through the discussions to be of crucial value to encourage transformation across sectors. We have been collecting data for decades, however, we need better systems to allow using these data in a meaningful way (e.g. in healthcare), by simulating and evaluating future visions in combination with physical capabilities like sensors and systems to provide real time information. With regard to emerging technologies, such as AI, robotics and quantum computing, it was highlighted that context is key and there is a requirement for responsible and ethical leadership, and a need for broader skills such as knowledge of software architecture and its regulatory environment.

The need for working systems-of-systems was emphasised. Currently, there are many individual systems, but there are technical challenges in creating a system-of-systems. Innovation in sensors can help to understand how complex systems work but it is challenging to replicate the conditions in a lab; a full-scale approach is needed. In addition, a system of systems would include integrity, ethics, safety of systems, understanding consequences, and would be informed by data-centric engineering.

Finally, there was a requirement to ensure challenges do not become too segmented, linking Engineering with the social sciences and to have a consideration of the global landscape of Engineering. We collectively need to determine what character research should have to make it ready for policy input and implementation.

2. **What are the new skills and knowledge that your members will need to gain to make sure they are competent (the context being that members all need to act within an ethical framework to protect and support society)?**

Skills were raised as important factor to achieve impacts against the pressing challenge that is climate change. These span from technical skills like carrying out net-zero assessments, sustainability training, life cycle analysis, costing assessment and risk analysis to consider acute and chronic risks to people and the planet, including hazards traditionally not in the engineering domain (e.g. climate impacts, social inequality, loss of biodiversity), to more social aspects of the challenges. People coming into engineering need to be competent and have an appreciation of where engineering lies in terms of sustainable development. This includes effective societal and public engagement and ethical decision making.

An essential aspect of addressing Tomorrow's Engineering Research Challenges is cultivating the future talent today, but the question remains where the next generation of scientists and engineers is going to come from in sufficient numbers. The acquisition of new skills or reskilling should be a priority for the engineering community and the UK Government. The education sector needs to offer better guidance and funded training for young people, so that they are better prepared and equipped with the appropriate skills for the roles that employers need to fill. It is important that the priorities address the skill needs of the engineering community. These needs include, but are not limited to: fellowships for researchers of the future cultivating agility and impact; skills at all levels starting from apprenticeships, with an environment conducive to advancement and retention; retraining and upskilling trained people within industries and retraining areas at risk of skill loss (e.g. oil and gas, foundation industries); digital literacy; communication skills; skills to work seamlessly across disciplines; digital and green skills and social aspects of engineering. There are further requirements to accommodating relevant academic courses, whilst paying attention to recruit, develop and retain teaching staff. The participants added that it is important to instil at the formation level (e.g. undergraduate degree) the capacity for life-long learning, as it is likely that those in education now will, in 10-15 years, l be using technologies and processes that have not been invented yet. It is essential to ensure that relevant Continuing Professional Development (CPD) at all levels and career stages is used to bring in new technologies and outcomes of future research to the workforce.

In addition to skills and training, inclusive practices throughout the engineering profession are essential. All Professional Engineering Institutions recognised the need to attract young people from all backgrounds into engineering, noting how important diversity is to fostering creativity and innovation. Many talented people do not see engineering as a potential career path, due to outdated misconceptions of what engineering is, which is a great loss for the sector. Engineering should be presented in the compulsory curriculum to increase visibility including with young people from disadvantaged backgrounds who often do not get that exposure. In addition, it was noted that when making career choices, young people place value on making a positive difference to society and the environment. Therefore, it is important that engineers and industry are closely connected to the development of standards and delivering outreach, and that the positive impact of engineering against global challenges is communicated.

The final emerging theme was to have a global approach on the technology landscape and development of new technologies. This will have a significant impact on the way new technology is developed and implemented in the UK. As part of the analysis of global trends, the UK should look to the global organisations that set standards for new technologies and should consider how the UK engineering community can develop and influence these standards to allow the UK to gain greater competitive advantage, in particular regarding exporting new technology. Existing gaps in global standards and best practice can already be found in areas such battery storage, hydrogen and digitisation across transport sectors, and with the rapid growth of new technologies to tackle climate change, new and agreed global engineering and technology standards will be necessary going forward.

Early Career Researchers

Early career researchers (ECRs) represent the future of engineering research and development. Within the next 10-15 years, they will be the inventors, creators, visionaries and leaders of a future that could embed engineering principles and practices in many of the challenges identified. For this roundtable we brought together members of EPSRC's Engineering Early Career Forum. During the discussion the participants shared their views on the most important future grand challenges and the skills and support ECRs need to have in order to contribute to addressing them. Responses to the questions highlighted major themes on sustainability, achieving net zero and resilience:

1. **Looking 10-15 years into the future, what do you consider to be the most interesting challenges within the field of engineering that we should be exploring?**

Climate change is bringing major challenges and engineering needs to provide novel solutions for energy consumption, reducing fossil fuel use, sustainable and efficient material use, and ensuring infrastructure can cope with environmental challenges and larger populations. Reducing emissions should be the priority for high-emitting sectors like construction, and more focus should be placed on the consequences of rare-earth mining. In addition, repair strategies for failing to reach environmental targets in time need to be in place.

The scale of the challenges requires working together and keeping a global perspective, giving priority on protecting the planet. Engineering needs to be sustainable and human-centred and needs to keep pace with evolving challenges and global inequalities.

AI, robotics and machine learning also emerged from this discussion as important engineering challenges for the next 10-15 years. Emphasis was given in the need for better communication of those technologies, their powers, and their limitations, to the public. We are at a point where we are creating so much data that we do not understand, and AI and machine learning can possibly help us understand the data we already have. However, the idea that machine learning is the answer to everything is a misconception. There is still a lot of fundamental research needed and while data and AI training needs to be commonplace across engineering, the fundamental engineering skills are still essential.

Discussions focussed on healthcare, and the need for cross-disciplinarity approaches and to have a global lens. Participants noted that it is crucial for engineering focussing on healthcare-related technologies to include the clinician and end-user perspectives to enable translation of research into practice. Healthcare research also needs to be international, and we need to work alongside developing countries to solve global health problems, taking care to foster a two-way communication instead of presenting ourselves as having all the answers.

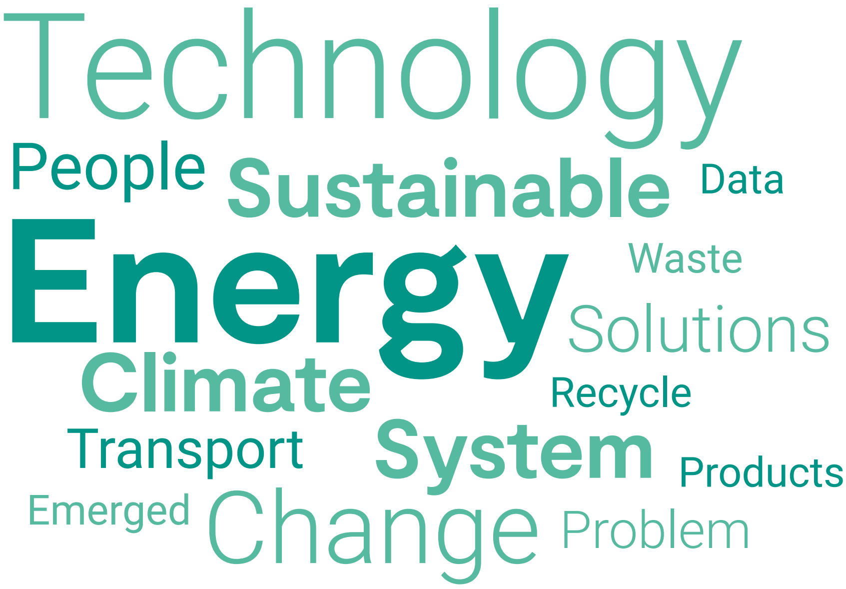
Significant engineering challenges also exist in transport, which is at the cusp of a revolution, driven by electric vehicles, robotics and autonomous systems. These will have significant effects on the urban landscapes, for example, by exposing urban communities to non-traditional sounds like the noise of drones, or by being practically silent like e-vehicles, with associated safety challenges. At the same time e-mobility offers the opportunity to change the way we address environmental noise problems.

2. **What skills and knowledge do you think ECR's need to focus on having now to be able to contribute to addressing these challenges going forward and what support do they need to be able to gain that?**

ECR's need wider foundations of knowledge within and outside of STEM, as well as training to develop broader industrial, commercial and policy awareness. Participants highlighted that movement between academia and industry is challenging because the required skills often do not match (lack of published papers if coming from industry, or lack of industry experience from academic background). In addition, the rapid pace of technological changes leads to an under-skilled workforce, so professional development training is needed, and more efforts should be made on retaining talent in engineering and making research a more appealing career. Participants noted the need for training to understand interdependencies between design, performance, functionality and impact on people, and the need to consider long term consequences during the development process and not after technology has been developed. Linking to that, the need for testing public acceptance of ideas, as well as scientific feasibility was raised. Emphasis was placed on improving cross-disciplinary working skills and having a systems approach towards future challenges. Participants highlighted the importance of encouraging people from different backgrounds in engineering and at the same time embracing applying engineering knowledge to new areas, which could be done by promoting secondments and short exchange programmes into other disciplines.

To promote ECR development the participants noted the need for EDI practices and support in developing their research vision. To allow ECRs to develop ideas freely, with broader vision and new collaborations, the ingrained hierarchy in engineering needs to be challenged. Opportunities to network and influence (such as through Early Career Forums) are beneficial, but as noted, they are few and far between. Diversity and inclusion were highlighted as key issues for engineering and education institutions. Professional bodies and funders have a role in implementing inclusive practices (e.g. eliminating bias in review) and encouraging sector-wide change. In the views of ECRs, funding opportunities should value novelty and usefulness of research equally, which could further promote private investment in research. Focus was placed on enabling research that breaks down silos and encourages communication between disciplines. It was noted that few schemes welcome truly multidisciplinary research currently, and that more of this should be encouraged, especially between engineering and social sciences. Specific suggestions for attractive funding opportunities included policy fellowships, Knowledge Transfer Partnerships, support for developing international collaborations, and Centres for Doctoral Training aimed at global challenges research.

PhD Students



PhD students, through pioneering their own focused subjects, often break new ground and therefore form part of the cutting edge of research. There are thousands of PhD students studying engineering in the UK. Without this next generation we won't solve the problems of the future.

For this roundtable we brought together engineering PhD students from across EPSRC-sponsored Centres for Doctoral Training (CDTs). In responding to the questions, the participants highlighted sustainability and the move to cleaner energy technologies as key areas, but also noted the need for engineering research to serve a purpose and contribute towards societal benefit (which requires bringing disciplines together, including economists and policy makers), to address complex problems, as well as to promote more collaboration between academia and industry:

1. **From your perspective, looking 10-15 years in the future, what do you consider to be the most important Engineering research challenges?**

Dealing with the climate crisis emerged as a key challenge. Providing sustainable solutions for energy generation, transport, infrastructure, housing, food and water supply were noted as key areas for engineering research, as were finding further ways to implement circular economy by recycling, reusing and repurposing materials, equipment and technologies.

The important role of engineering in the field of regenerative medicine, where novel biomaterials with very specific formulations are needed, was also highlighted. Participants noted the need for research to serve a purpose and contribute towards societal benefit, which requires bringing disciplines together, including economists and policy makers, to address complex problems, as well as more collaboration between academia and industry. Participants underlined the need for standardisation of terminology, especially in emerging fields, to ensure research is reproducible and progress accelerated. Finally, participants highlighted the importance of maintaining and expanding global networks and keeping a global view in research.

2. **What do you think should be done to encourage more people to pursue a PhD in engineering and cultivate the UK engineering talent?**

One of the main topics that was highlighted during the roundtable was the importance of encouraging more people to pursue a PhD in engineering. There is a need to raise awareness within the undergraduate community of what a PhD is, what it entails and what career pathways it can open. Offering opportunities for undergraduate students to have exposure to research during their courses, such as through internships, was also suggested. This was highlighted as an effective way to increase interest in research, but advice was that these opportunities should be paid, so that they are accessible to people from all socio-economic backgrounds and situations. The importance of outreach to younger ages was also mentioned to plant the seeds for interest and passion for science (and research) from an early age. This kind of outreach is sometimes undertaken by

PhD students, and so it was noted that it would be beneficial if PhD students were further encouraged and supported to pursue those activities. Another point that was raised was encouraging mobility between academia and industry in order to further open the pathway for pursuing a PhD to people from industry who are interested in doing research. Such mobility would also offer PhD students the skills, networks and insight to be able to transition to industry after their PhD. It was highlighted that offering a more competitive stipend for PhD would increase the chances of attracting interest from more people, including those from industry. Finally, creating welcoming environments that make people feel safe and paying attention to mental health were noted as ways to attract and cultivate engineering talent.

3. **What do you think are the main threats and opportunities for people pursuing a career in engineering research?**

Participants agreed that one of the main threats to pursuing a PhD is the lack of competitiveness of the stipend when compared to a graduate job salary. PhD students are adults with responsibilities, such as families or a mortgage, but they are sometimes classed as students. They have to compete with undergraduate students for student accommodation and at the same time they might not qualify for house sharing for professionals. One of the implications of this is increased difficulty in finding housing, especially in an economic environment of increasing costs of living. Another pertinent perception was that a PhD graduate might be offered the same salary as a holder of an undergraduate degree when looking at jobs in the industry, thus not seeing their more developed skills as being valued. This can create a feeling of falling behind, compared to peers who go straight from undergraduate degrees into an industry job. This makes studying for a PhD, and by consequence a career in research, less attractive for some. The PhD students consulted highlighted that one of the main reasons for not continuing in academic research is the instability and insecurity of postdoctoral positions that the lack of permanent contracts creates, particularly in the face of family and financial responsibilities.

When discussing careers in engineering research, the participants noted that there are many opportunities to do valuable work and creating positive change in people's lives. They meet like-minded people and collaborate with people from other research fields. They do benefit from the opportunities to increase collaboration with external partners, such as industry, as well as collaboration between PhD students working on complex projects each focusing on their own expertise. Working with peers, as opposed to working in isolation, was identified as a way to battle stress and the impostor syndrome, which students often experience especially when working on complex cross-disciplinary problems that might not exactly match their training background. They noted that collaborative projects with industry can be mutually beneficial for students, for example by doing small scale testing that industrial partners can then scale up, and industry offering technology that can advance their research further. Participants found the opportunities for cross-disciplinary training through their CDTs valuable, noting it gave them a more holistic understanding of their projects, but saw an opportunity for offering more of those options, for example by allowing students to choose some of the modules offered through their institutions in different disciplines. It was highlighted that engineering research is a very creative route and research careers are stimulating, diverse and flexible. The latter was highlighted as an important benefit for neurodivergent people according to the experience of participants and their peers.

Engineering EDI Groups

Engineering is a diverse discipline which requires an equally diverse workforce. Diverse workforces improve innovation, creativity, productivity, resilience and market insight. The UK's current engineering workforce lacks diversity and there is a national imperative for change.[3] We convened a number of individuals representing Engineering EDI groups to canvas their opinions on Tomorrow's Engineering Research Challenges.

The EDI roundtable discussion focused firstly on extracting the most important engineering research challenges for the next 10-15 years, and then on identifying the barriers under-represented groups face in fully participating in addressing the challenges with suggestions of what can be done to remove them to enable an equal, diverse and inclusive engineering ecosystem:

1. **From your perspective, looking 10-15 years in the future, what do you consider to be the most important Engineering research challenges?**

Human resilience in the face of unprecedented challenges, such as climate change and global health crises, was noted as one the main challenges for the next 10-15 years. The engineering sector was highlighted as having an important role to play in providing the tools, skills and means for humans to cope with the challenges and mitigate the effects, through technologies for green energy, energy transition, decarbonisation, carbon sequestration and healthcare technologies. Engineers should be sustainability and socially conscious to provide the solutions for clean air and clean water for all, sustainable food production for a growing population, and equity of resources.

Engineering will also be important to improve healthcare in ways that are faster, more efficient and more equitable, through technologies such as advanced health informatics and innovations for personalised medicine.

To ensure engineering outcomes are inclusive, the role of engineers in society needs to be reframed. Engineering research should be co-created with the end users and beneficiaries and designed to be future proof and fit for purpose. This should not only be done with a UK perspective, but it should take into account the challenges that global populations face, adopting a global perspective, and ensuring those most affected have meaningful representation and a stake in that research.

The rapid advancements in digital technologies provide many opportunities in the future, but also come with the challenge to ensure the ethical and policy frameworks keep up with the pace of change to protect societal cohesiveness.

In addition, engineering problems are becoming more and more complex, so there is a challenge to break the siloes and enable truly multidisciplinary research in order to provide heterogenous solutions

[3] https://www.engineeringuk.com/media/232364/edi-strategy-final.pdf

for heterogenous populations. To meet future needs it will be important to create the environment that will bring existing scientists, researchers, PhD students and students to research in the right way and find the ways to provide resilient and personalised remote and hybrid teaching and education. There is also a challenge with regard to maximising impact and enabling this to ensure research is translated into commercial applications with the aim to improve people's lives.

2a. Thinking about these research challenges, what do you consider to be the main barriers under-represented groups face in fully participating in addressing them?

Engineering is still a very male- dominated environment and training programmes are often not inclusively constructed. People from under-represented groups feel they have to face hostile environments, power structures that put them in pre-constructed categories, and an unwillingness to adapt the status quo, which perpetuates the leaky pipeline problem and makes participation in research much more difficult for minority groups. As shown by data[4] there is a gender gap in the value of awards applied for, showing that women apply for smaller grants, which by consequence means having to apply for more grants that can lead to burn out. Moreover, there is often a disparity in the contracts offered, with women offered less opportunities for research contracts, as well as a difficulty to return to research after career breaks. For under-represented groups, lack of visible role models, implicit biases in the recruitment processes, and lack of access to networks of experts represent barriers for involvement. In addition, there are further barriers towards researchers from minority backgrounds where lack of partnerships with Global South academics, poor use of tools to democratically and effectively consult with stakeholders and lack of access to funding for minority-led organisations are apparent. Another point raised was that the shift towards hybrid working creates a risk of disadvantaging people in earlier stages of their career who would benefit more from the impromptu opportunities for networking in the workplace, as well as those who might have to work from home more often, for example due to caring responsibilities. When it comes to commercialisation of research, it is noted that there is a lack of data and intelligence to understand the diversity make-up of the population receiving those opportunities, but according to existing data5 women are under-represented, indicating the existence of gender bias in the investment landscape. Fixed term contracts for early career researchers create insecurity, which dissuades people from pursuing those entrepreneurship opportunities. Finally, it was noted that another barrier communities face is the differential value that is put on the information and outputs created depending on where they are coming from.

2b. What do you think can be done to remove those barriers and enable an equal, diverse and representative engineering ecosystem where under-represented groups can contribute equally to the future engineering solutions?

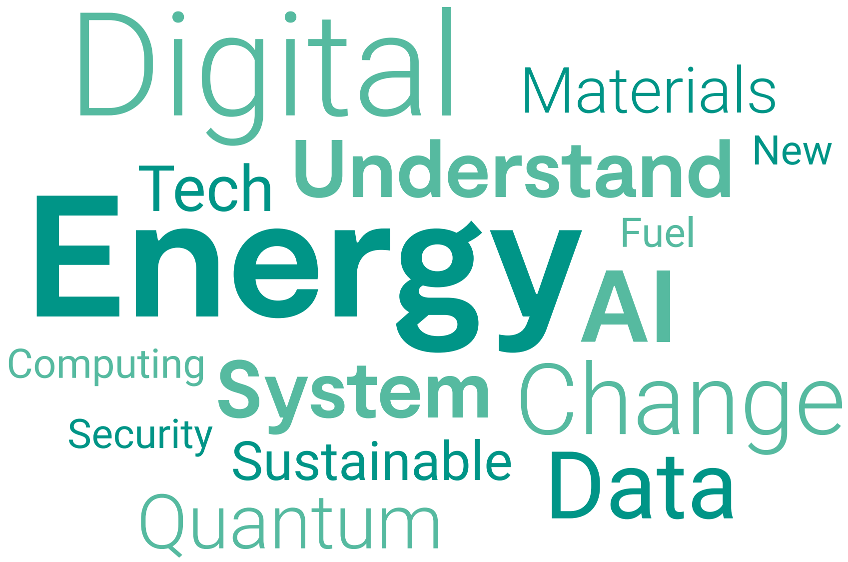
The group responded by stating that we are at a point where the barriers facing under-represented groups are reasonably well understood. Whilst more understanding is still needed, action is what is needed; there is a need for accountability, transparency, fairness and more education to challenge harmful stereotypes, and there is a need to challenge the effect of groupthink and the misconception that creating equitable systems means lowering the bar. It was noted that engineering degrees need to be redesigned with EDI embedded to give under-represented groups a higher sense of belonging, which in the long term will attract more talent from under-represented groups in engineering. It was also noted that there is a lot of improvement needed requiring systemic change with individualized adjustments and appropriate investment in terms of money and resources, to provide disability inclusive practices that are fit for purpose. It was highlighted that communication with diverse communities about research must be improved, and the group proposed ways to facilitate that including collaborations with organisations and channels that already have relationships of trust built with those communities.

[4] https://www.engineeringuk.com/media/232364/edi-strategy-final.pdf

More efforts should also be made to ensure the available career and research pathways and opportunities are communicated widely throughout society. To that end, an intervention that describes ‘National Pathways’ to hold all the information in one place, similar to the NHS health pages, was proposed. To provide more opportunities for career progression, schemes like mentoring programmes and career development funds for under-represented groups were also suggested. In order to address structural barriers, there is a need for work at an institutional level to agree a collective framework on what data and intelligence needs to be collected in a consistent way. This will allow institutions to self-reflect and draw meaningful conclusions to identify the actions that need to be taken to create more inclusive environments and practices. To facilitate the adoption of inclusive practices as widely as possible, a strongly supported idea was to provide incentives including making institutional diversity plans a requirement for funding, but also positive action such as providing rewards linked to inclusive practices.

Finally, it was highlighted that it is important to showcase the opportunity that EDI creates for the engineering sector and engineering research. Inclusive practices allow the community to tap into a larger pool of talent and diverse research teams inherently have a diversity of thought that enhances the outputs and impact achieved from grants.

Industry (1)



The engineering industry faces many challenges as technology rapidly evolves and the global population quickly increases. Our current and future industrial landscape has a key role to maintain and sustain many crucial aspects of our lives as well as to support a skilled and diverse workforce.

The roundtable discussions among senior representatives from industry focused on the main engineering challenges for the next 10-15 years and the skills required to help industry achieve impact through these challenges, and ways in which academic research can enable this. The responses from the first roundtable, which brought together representatives from aerospace, automotive, defence, foundation industries and power sectors, are summarised below.

1. **Looking 10-15 years into the future, what are the areas of impact and Engineering challenges you aim to focus on?**

Energy transition and sustainability were identified as key challenges for the UK industry. Distinct challenges include the urgent requirement to reduce energy in manufacturing, convert to new, sustainable fuels and adapt existing assets to use these, deal with exhaust emissions and implement recyclability and efficiency throughout the manufacturing process to achieving net zero and a circular economy. The complexity of these challenges and the pace required for adoption poses an existential threat for whole industries. Engineering can advance ways to 'green' and expand the energy supply by utilising new fuels and develop technologies for storage, delivery and management. Hydrogen, fusion and fission offer exciting opportunities for the future, providing the social acceptance is progressed and the cost and security of energy transmission is kept manageable. To achieve a sustainable future, renewable technology and responsible use of materials are key. The challenges to enable this are acquiring a better understanding of energy requirements and reducing our dependence on scarce raw materials. Engineering research is at the heart of those challenges and through having a greater awareness of environmental impact, Engineers will be able to advance sustainable practices across sectors (e.g. from manufacturing to agriculture to space) to realise a circular economy.

Challenges relating to digitalisation and new technologies emerged through the discussions. The digital future will be shaped by advances in exascale computing, engineering biology, quantum technologies, AI and cyber-physical infrastructure. There is an abundance of collected data, as well as continuous data collection, and to harness the information therein expert systems are required in order to be able to simulate and evaluate practices for the future (e.g. for personalised healthcare). This progression requires advances in computing capabilities, cloud edge computing, AI for learning and controlling, digital twins, internet of things and cyber-physical interfaces. Focus is needed on advancing underpinning capabilities, such as superconducting at higher temperatures, and resolving bandwidth issues to allow progressing from 5G to 6G and embed connectivity. To build complexity into products, systems engineering understanding is needed. Trust is another key element in a digital future. Embedding cyber-vulnerability awareness in digital skills, providing digital certification for products (e.g. aircraft), and understanding how autonomous machines and humans interact, are needed to create trustworthy systems. Furthermore, in an environment which includes legacy assets and future assets, intelligent regulation is needed to manage critical and complex systems, ranging from supply chains, manufacturing and repair, autonomous systems, and healthcare.

2 **What skills and knowledge are necessary to help you achieve that impact and how can academic researchers and the EPSRC enable this?**

Digital and systems skills, as well the ability to work across disciplines, emerged as key skills for future engineers. Participants noted that at the current pace of change there is a lack of appropriately skilled science, technology, engineering and mathematics (STEM) graduates to employ. The group highlighted the importance of including systems engineering, data science, machine learning, quantum technologies, AI and autonomy in curricula, as well as upskilling the workforce at a high pace. Softer skills, such as having awareness of the big picture, and the ability to bring disciplines together were also emphasised. To allow engineers to build that broader range of skills, there is a need to join up industry and academia to facilitate skill exchange. This can be done through industry support for doctoral training and other university/apprenticeship training schemes. To enhance those collaborations, encouragement of flexible engineering career pathways, as well as a better understanding of how to work together (e.g. in managing IP issues) are needed. In addition, participants noted that an important issue to address in the engineering workforce is the lack of diversity, which further exacerbates the skills gap, and highlighted the need for more diverse role models and activities to encourage a more diverse workforce.

The participants emphasised that the UK has excellent academic research, but to achieve maximum impact this research needs to be aligned and coordinated, and opportunities for industry to co-invest and achieve commercial and economic impact need to be promoted. Collaboration between funders of different technology readiness levels (TRL) needs to be enhanced to provide funding that links TRL 0-6, and research models that allow for speed and agility need to be available. To encourage more young people into engineering, the public and policy awareness in engineering needs to be developed. This includes social and economic innovation, expanding to new applications, and commercialisation of research through licensing and spin outs. UKRI can play a role in fostering collaboration and impact, through launching partner programmes bridging academic innovations to application development, looking into more disruptive technologies, and providing incentives for networks and open science.

Industry (2)

The second industry roundtable brought together representatives from construction, water, renewables, pharmaceuticals, and manufacturing sectors. Many of the topics that emerged through the discussion align with the outputs of the first industry roundtable, demonstrating common needs across sectors:

1. **Looking 10-15 years into the future, what are the areas of impact and Engineering challenges you aim to focus on?**

Data and digitalisation came through as an important challenge for industry, which needs to deliver industry 4.0, including digital twins, the definition of which is currently amorphous. The industry faces the question of how to move from legacy assets, and greater use of data is seen as a key enabler. Digitisation, convergence of technologies, automation and robotics, are all bringing rapid change. Supply chains face challenges such as those relating to digital factories with integrated automation, translation of data, supply neural networks and guaranteeing provenance for trust and transparency. These challenges create the need for systems thinking to connect the various elements and data-centred engineering to focus on cloud data infrastructure in addition to governing ethical frameworks.

Sustainability was another major theme in the discussion, spanning from energy efficiency and new materials to safe and affordable water for all. In order to achieve net zero goals, whole life-cycle processes need to be redesigned and energy resilience and efficiency should be embedded across sectors. Despite the commitment, there are many unknowns around this including the behavioural element on how users will uptake new technologies. Strategies like internal carbon pricing, which has been gaining attention in recent years, adopting different technological approaches such as nature-based solutions, and finding responses to planned obsolescence, were highlighted by the participants.

The design process was highlighted as a key element for transformation and one that casts a big shadow on net zero. Industry needs to have excellent design processes so that they are able to have control of the supply chains. Supply chains are complex interconnected systems, with lots of inputs and beneficiaries, and a plethora of new materials and technologies. However, what is missing is an accelerated way to test and trust the data available and this creates a bottleneck for innovation. Therefore, finding ways to test, assure and validate is important and when industry knowledge reaches its limits, academia has a role in helping shape the full picture.

Sector specific challenges were also discussed. In offshore wind, industrial deployment at the rate of change needed in the energy sector is bringing challenges around the design approach, operation and management (O&M) and energy storage. The industry is looking at advanced manufacturing for larger, floating wind technologies, full-scale validation to predict early failures, fully predictive digitalised O&M and robotic deployment for inspection, maintenance, and repair. In manufacturing, new modalities and digital and complex products, are emphasising the need for engineers to engage more in human-centred design. In the food sector, the challenge is to provide food security for all and produce sustainably. It was noted that currently a majority of food supply comes from a very small number of animal and plant species, and whilst the movement of plant-based foods is increasing, this is creating appetite to diversify the foods produced by large food companies. Adoption of regenerative agricultural practices can make agriculture more sustainable, but there are engineering challenges in bringing these through the whole supply chain. In healthcare and pharmaceutical technologies, bridging between sciences such as chemical engineering, synthetic biology, robotics and AI was highlighted to understand the impacts of holistic healthcare, including diagnostics, personalisation, and wearable technologies. In personalised medicine, there are challenges on commercialisation practices to ensure the outputs are significantly robust, and on adapting the manufacturing process. In the healthcare sector there are a large number of SMEs including non-traditional healthcare disciplines like robotics, image and vision computing and AI. There is a need for more engineers who can contribute to medical innovations. Challenges relating to the future built environment were also discussed where priority themes included adopting circular economy principles, enhancing resilience, safety, and health and well-being. Safety and quality of the built environment are active areas for research and development investment in the construction sector, with topics ranging from low carbon construction methods, material characterisation, digitalisation and getting value from data. The challenges require involving industry, working with the market, and enabling cross-disciplinary collaboration, such as linking engineering more closely with the social sciences. In the transport sector, specific challenges focused on being prepared for a mixed vehicle fleet that includes autonomous vehicles, managing old infrastructure and realising data-driven mobility to better integrate rail, freight and aviation. All of these need to be with sustainability and green energy principles in mind, as well as environmental concerns such as improving air quality and protecting biodiversity.

2. **What skills and knowledge are necessary to help you achieve that impact and how can academic researchers and the EPSRC enable this?**

The discussion highlighted the importance of data skills for engineers as the industry needs engineers that can understand, navigate, and use data, as well as those who are cyber-security aware. The need to revolutionise assurance was also discussed and noted as a huge gap in the workforce. It was noted that internationally there has been focus on the underpinning tools and techniques required for industry, such as non-destructive evaluation (which is needed if we are to realise Industry 4.0) and the skills requirements for the global engineering sector. The current thinking suggests four new roles: systems developer, caretaker, decision maker, and user experience (UX) designer. Soft skills such as creative thinking, adaptability, thought leadership, entrepreneurship, and the ability to work with different disciplines were emphasised, especially given the complex challenges of reaching net zero targets. Consideration is therefore required on how to e nhance exposure of engineers to those skills. Finally, inclusion and diversity were identified as focal points for industry. Diverse talent is needed in organisations to bring social value, creativity, problem solving nd leadership of change, as well as diverse and inclusive outcomes.

Industries are continually faced with transformation and research can help industry understand and fill the important gaps of knowledge. This implies a need to mobilise the whole community. It is important that the support for underpinning technology is not forgotten and that future engineering research looks outside the traditional engineering spaces, such as to social science and behavioural scientists, and breaks down silos to bring integration and co-creation.

Chief Scientific Advisors

The UK Government's network of Chief Scientific Advisors (CSAs) form a cohort of thought leaders and experts to inform all government departments on science, engineering and technology issues. The CSAs provided key contributions during our engagement and focussed perspectives on the future Engineering research and development challenges:

1. **From your perspective, looking 10-15 years in the future, what do you consider to be the most important Engineering research challenges?**

Net zero and climate change were strongly highlighted as engineering challenges that need to be undertaken at scale if we are to ensure resilience to change. Solutions that couple with nature are therefore important, but we need to ensure that we do not worsen things environmentally by adopting engineering solutions that contrast this. There are research opportunities to provide reliable and sufficient grid-scale energy storage, reduce the carbon content of steel and concrete production and maximise reuse and recovery of infrastructure and materials. Some of the major sustainability challenges for the UK that were highlighted were related to materials efficiency of use, recycling of metals and precious metals, access to and processing of rare-earth elements and security of supply chains from reputable, sustainable and non-oppressive regimes. Also, looking for variable feedstocks for fuel to generate grid specification methane or food grade carbon dioxide presents a specific challenge to cater for variations in feedstock and fluctuations in economic product mix whilst maintaining safety. In terms of food sustainability, engineering has a role to play in advancing precision farming and the growing use of robotics and automation in the agricultural sector.

Many of the new challenges over the next 10-15 years will not be related to new technologies, but instead about how we slow degradation of existing infrastructure (e.g. national grid, roads, rail, etc) and keep this in working order in the face of increasing economic pressures. The public will expect resilient transport, energy, water and waste, digital communications infrastructure, so longer-term research should be interlinked with regulation, as opposed to being swung by short-term political considerations. This presents an opportunity to use emerging technologies, such as AI, to undertake mundane design of typical infrastructure elements (providing that a risk-based framework in employed), to free up engineers to be more creative and demanding in their designs and focus on safety considerations.

Transport itself will soon become an integration challenge as we are increasingly seeing aspects of our transport system that were only physical becoming more digital. In this scenario, security and resilience considerations become more relevant. Of course, reducing transport carbon remains a significant challenge, not only addressing barriers to the generation, transmission and storage of green hydrogen or finding novel solutions of addressing growing electricity demand without enormous expenditure on power distribution, but also reducing the embodied carbon content of new vehicles and exploring technical solutions to increase car-sharing and active travel.

A cross-cutting theme that emerged was the need to understand and apply 'Big Data' techniques to engineering challenges, particularly to enable digital twins. Access to data is critical for effective research and better exchanges of data will foster the frontiers of innovation but also test public, private as well as international boundaries. Cyber-physical systems and addressing human considerations embedded in systems will enable us to mainstream systems beyond traditional engineering. There is also a need to define new approaches (akin to regular software updates) to ensure safety in increasingly interconnected complex computer systems over their entire lifetime.

2. **Thinking about these research challenges, what do you consider to be the main enablers and the main barriers in addressing them? What do you think can be done to remove the barriers?**

The CSA group emphasised a strong focus on people, not only encouraging young people to become engineers, but also how we empower qualified engineers to apply their skills to other sectors and ensuring engineers are distributed across the system to lead to successful deployment of technologies. Other barriers to deployment of new technologies could be overcome by learning from experiences in the past, such as involving regulators in early-stage development, so that intelligent regulatory frameworks can be put in place. Adopting this approach, particularly in areas that have not used it before, may inform our ability to deploy technologies faster and more effectively.

Whilst we should not forget the regional dimension of engineering in the UK and how efficient solutions could be employed in shipbuilding, renewable energy and oil and gas, many challenges are unlikely to be UK-centric and ought to be viewed with a global perspective. There is also the point about being able to engineer as simply as you can (which is pertinent for developing countries) but the challenge is about reducing complexity in systems to increase efficiency and reduce demand (on materials etc). Also, the issue of scale was revisited as it is vital to achieve impact and deliver cost effective solutions. The importance of international collaboration to achieve optimal scale, adoption and resilience needs more attention. Specifically, for longer term challenges, this means establishing international scale research and standards.

The group explored and challenged the traditional perception and practice of engineering, since it can often be siloed and focussed on top-down solutions. Engineering is and should be seen as an interdisciplinary 'science' and a method to transition science into solutions, since a number of areas of science have reached the stage where the problem becomes an engineering one. There is significant value in crossing-over with other disciplines to create more distributed solutions that are emergent and bottom-up. However, this raises a complex problem of bringing together multiple teams from different disciplines, which requires thought to achieve it effectively.

Engineering solutions should be considered in a more societal context, appreciating the complexity with engineering delivering for people's needs. This brings in the interdisciplinary angle, which could increasingly benefit many challenges. For example, Engineering could adopt more exploratory and goal-directed design by involving the arts community which could potentially bring in more creativity. And a standout challenge to grasp is the public perception of the new technologies that will facilitate net zero – whether it is solar farms, fusion power, electric vehicles – the UK Government, industry and Engineers need to work together to win public trust, without which progress becomes slow and erodes business confidence and return on investment.

Finally, the question was raised on whether Engineering should retain itself as a discipline as there may be benefit in combining aspects of science with engineering or expanding engineering boundaries. The group encouraged us as a nation to challenge the bounds of Engineering. Herein is an opportunity for the UK to frame our science and engineering towards innovation, creating companies and products and we should be positioning our young engineers to be entrepreneurial to enable this - to ensure we are fit for the future, and not dwelling on short term considerations. Thus, not only do we need to develop research to create a new and different professional culture but we need to be much more porous to arts and creative design models. By extension, we need to develop engineers who are comfortable working across the boundaries of science disciplines to get out of the traditional silo structure. Our future engineers need to understand that almost every system is socio-technical – it has humans in the loop and so must work with human behaviour and idiosyncrasies. This extends into the education sector where there is consideration of what skills our future engineers need to adopt the latest technologies, technique and the abilities to use the latest equipment (in the right environment). Funders and supporters of engineering research are required to embrace this wider flexible view of Engineering.

International Perspectives

To provide an international perspective, we engaged with representatives from selected national academies and academic institutions across the world. Their responses to the key questions helped to provide a global context to Tomorrow's Engineering Research Challenges:

1. **From your perspective, looking 10-15 years in the future, what do you consider to be the most important Engineering research challenges?**

The climate was identified as an important challenge for engineers to address, particularly the impacts of climate change, such as maintaining constructed and natural environments, protecting the oceans and carbon abatement and mitigation (specifically reducing and removing carbon). More specifically, members of the international community believed that some of the more fundamental and expansive challenges will be in the realm of better engagement with complex adaptive systems, as in energy transitions to address climate change that has asynchronous impacts on communities and corporations. Any responsible measure, be it efficient manufacturing or effective waste management, will require and necessarily build on a sound understanding and adaptation of systems engineering practices. The continuing need to learn from natural processes to guide the evolution of systems design, operations, and maintenance will be a fruitful and challenging arena for research.

For geotechnical and other civil engineers specifically, there are many related research problems over the next 15 years involving climate change, including addressing water shortages, maintaining transportation and other infrastructure (buildings, dams, water treatment plants etc), and addressing risks associated with natural disasters such as mud, rock and other landslides, loss of permafrost, threats to coastlines (from sea level rise and storm events), flooding along rivers, and ground movements associated with groundwater changes (rises or falls in groundwater levels). As regards water dams, the engineering challenges for the future will be the impact of climate change on hydrology and adaptation measures to ensure safety in dam operations.
Other technical challenges include the aging of these structures that will require innovative monitoring and rehabilitation techniques, development of new technologies that can be efficiently integrated into brownfield sites, new energy market models that enable distributed generation to play a larger role and multidomain approaches to energy systems (e.g. heating, electricity, hydrogen, demand side management).

Engineering can also deliver solutions to help us in preparing for the next pandemic, and the convergence of communication, control and computation for distributed systems. The integration of autonomous systems into environments where they are required to interact safely and efficiently with humans and development of frameworks to enable modelling of human behavioural and human trust for use in human autonomy teams was also highlighted. Such techniques will safely allow system adaptation within reasonable limits.

1. **Thinking about these research challenges, what do you consider to be the main enablers and the main barriers in addressing them? What do you think can be done to remove the barriers?**

A key barrier for systems engineering approaches is hyper-specialisation, notably in climate and health systems. While some degree of specialization is helpful, the inability to systematize concepts and insights from research and development will be challenging. A rich exposition of systems analytic concepts through case studies and cross disciplinary examples should be provided as a substrate for engineering students, not as an afterthought – our engineering graduates should be well versed in traditional systems thinking and appreciate the benefits and limitations of technologies like AI and machine learning.

In the years to come, engineering will be confronted by more complex, interconnected, diffuse and socially embedded issues, where it is almost impossible to set up the problem in terms of optimalisation as in the past. The fact is that engineering is not anymore confined to "science of artifacts", rather placed at the crossroads of "science of nature" and "science of human", and this line of thought can be captured in "Engineering in society and engineering for society", by paraphrasing "Science in society and science for society"[5] Therefore, it was considered that the identification of challenges will become most critical in the coming years.

Engineers need to have the capacity to identify challenges beyond the problem-solving and solution-providing lens. This approach calls for interdisciplinary effort, collaboration, co-creation, and co-evolution, all based on mutual respect among stakeholders. The ability in discovering challenges outside of traditional engineers' fields of expertise is also important and the process of engaging all stakeholders around potential challenges, facilitating discussing with them, exchanging ideas and working together will be essential to facilitate this shift.

The implication would be to revisit the current engineering education programs, mostly discipline-based and solution-oriented, by further integrating economic, environmental, human and societal dimensions, and the working practice in engineering fields, making it more inclusive and more evolutive.

The removal of political barriers to support true global collaboration and international partnerships, in addition to the provision of adequate funding were identified as obvious enablers.

[5] (Declaration on Science and the use of scientific knowledge, UNESCO, 1999).

Annex B:
Technological Challenges: Workshop Outputs

This Annex provides further detail to undergird the key questions in the Technological Challenges, drawn predominantly from the TERC workshops held in November and December 2021. Where appropriate, relevant stakeholder perspectives are integrated where they support and supplement the research questions. It should be acknowledged that there are many interconnections and overlaps between each of the Technological Challenges.

Space

Ensure **space research** is sustainable, and design and develop technologies that will be used to explore and sustain life in space and on Earth.

Q1: How can we harvest existing space-based resources (reusing and recycling where possible) to provide for humans to live in space?

To address this question, we must:

- Understand the water cycle in extreme environments, including on the surface of other worlds (e.g., how to maintain and/or sustain water to ensure there are no losses as well as understand the fundamental properties and behaviour in extreme environments);
- Determine the limitations of materials in extreme environments - including temperature, radiation, pressure;
- Determine the formation and limitations of soil to support locally sustainable civil engineering (including building materials with additive technology) and the growth of crops;
- Optimise launch and propulsion research to enable more sustainable transport
- Eliminate the need for rare, precious, and toxic materials in spacecraft and have the ability to recover valuable materials from redundant spacecraft;
- Understand how biochemistry and the physics of life works in space;
- Sufficiently develop quantum technologies to enhance and ensure digital twins (applied to space technologies) for simulation and testing before deployment;
- Make spacecraft and satellites demisable, or genuinely reusable (e.g., repurpose or recycle old satellites or redundant spacecraft to give them extended, continued service life).

Stakeholder Perspectives
There are opportunities in space debris removal and space-based energy

Q2: How can we use the extreme conditions in space as test beds for life here on Earth?

To address this question, we must:

- Increase reliability of electronic components and systems in extreme environments (vacuum, extreme heat/ cold, radiation, vibration, cosmic ray interactions with technology);
- Understand the physics of life in extreme environments (i.e. the fundamental properties of biomolecules under extreme physical and chemical conditions);
- Work out how to utilise robotics in space, such as considering modular manufacturing, assembly, maintenance and decommissioning or recycling of parts and systems in orbit or on other planets;
- Identify technologies that can transfer solar power from space (to Earth).
- Understand how cooling and heating of electronic systems works in the space environment (especially when exposed to intense solar radiation);
- Increase efficiency of power systems in space so they have excess power (which could be transferred or stored);
- Understand fundamental properties of coupled systems to enable modelling/ simulation tools;
- Harness big data (or even sparse engineering data) to enable workable digital twins (of the space environment);
- Prove, through simulations, that civil engineering projects are safe in extreme environments (what materials and boundary conditions?);
- Learn from British Antarctic Survey, the Royal Navy and the World Extreme Medicine Community on survival aspects in confined and extreme environments.

Stakeholder Perspectives
Opportunities to use our learning from using technology in space (e.g. remote sensing, navigation, communications)

Q3: How could space be used to help meet basic human needs, such as food, and provide a method for manufacturing of specialist items?

To address this question, we must:

- Understand the limitations of soil and agriculture (i.e. what crops will grow, what is the effect of radiation, do we need fertilisers or pesticides?);
- Develop safety systems (fire, biohazards etc) that can respond faster and better predict failures and develop autonomous mitigating actions;
- Understand the needs of long-term healthcare in space, such as manufacture of pharmaceuticals (operations of bioreactors and other chemical plants in zero gravity) maintaining physical, psychological, mental and social health and understanding how diseases and drugs work in space;
- Identify materials that can be locally extracted and used (e.g. mined from the moon, for use on the moon);
- Develop robotics that can operate autonomously in space (e.g. design for robotic maintenance and assembly).

Stakeholder Perspectives
Orbital manufacturing (making components in space); design and manufacture of space vehicles

To enable the research, we need

- A strong academic base
- A broader multidisciplinary UK Space Network (to enable collaborative environments) with those who are not currently working in space research.
- To recognise that space research begins on earth.
- World leading expertise and facilities in the UK (in academia and industry)
- To capture the public imagination (schools, future scientists and engineers)
- Lots of opportunities for many disciplines to work together in solving interesting and relevant problems
- To go beyond solving multiscale problems - and enable trans-scale (looking at ecological perspectives)
- To clarify and simplify the funding pathway; a joined-up, complementary, funding portfolio without gaps
- Links to UKSA, ESA (and NASA) and other leading space organisations globally.

Potential barriers include

- Lack of clear strategy and direction on funding fundamental space research
- The UK funding landscape is too complex/ fractured, non-continuous with big gaps between remits of funders
- Lack of mechanisms to engage with global space organisations
- Lack of integration with wider disciplines
- Understanding fundamental properties of coupled systems to enable modelling/ simulation tools.
- Harnessing big data (or even sparse engineering data) is a challenge currently to enable workable digital twins. There is a need for data fidelity, so we trust what we see.
- Lack of prioritisation; problem is too big - where do we start?
- Public perception is that space research has no benefit for them
- International competition vs cooperation
- Unclear ethics and legal policies
- Open research vs national security
- Bodies like UKRI and sister-global bodies must work towards depoliticising space.

Transportation Systems

Develop sustainable, integrated, and equitable **transportation systems**

Q1: How will we store, convert and distribute truly sustainable energy for transport and develop propulsive technologies to use that energy efficiently?

To address this question, we must:

- Have a process for reviewing current and future energy storage and propulsion technologies, and to develop these for transportation on a 'whole life' or systems basis as part of a wider integrated strategy;
- Be able to use the strategy to influence both UK and international policy for transport and energy development;
- Distribute fuel production, using local and national options, e.g. local solar powered hydrogen production, battery charging;
- Ensure a reliable energy delivery infrastructure, e.g., local, national grids, capable of delivering the overall energy demand and the peak power demands of transport;
- Develop long-range transport power options, e.g. drones/advanced air mobility, maritime, intermodal transport;
- Determine optimal fuel choice in the context of both the vehicle itself and the impact that fuel choice has on the wider energy system (whether this be electricity / gas etc);
- Reduce energy use through:- mass minimisation; light-weight materials; novel structural configurations; multifunctional materials/ structures and lessening mechanical and aerodynamic losses (across all modes);
- Maximise efficiency through gaining more efficient power transmission, mechanical energy storage, aerodynamic optimisation, active/ adaptive aerodynamics;
- Continue to increase efficiency through electrical machine design (to maximise power densities) and vehicle design, manufacture and operation with performance targets.

To enable the research, we need

- An excellent underlying UK capacity in transport research – energy storage and delivery, vehicles, networks, systems (world leading aerospace engineering for example)
- Broad existing awareness (within academia and increasingly within society and industry) of the importance of sustainability
- Large-scale/national level testing facilities (e.g. model town/city for properly exploring solutions in a realistic setting)
- To engage better with global policy making in transport, with better provision and linkage of data

Potential barriers include

- Technology options that are not compatible with the transportation system choices.
- The problem of scale and infrastructure – we won't know if certain approaches are good ideas until they have been implemented at scale, but scale requires infrastructure and is incredibly expensive

Stakeholder Perspectives

Future Transport relies on clean energy (hydrogen, batteries, sustainable fuels) or zero emission technologies, but there is a need to ensure manufacture is economical and transport of the fuel is efficient and safe.

Decarbonise existing transport by

- Addressing barriers to the generation, transmission and storage of zero-carbon hydrogen;
- Finding novel ways of addressing growing electricity demand without enormous expenditure on power distribution
- Reducing the embodied carbon content of new vehicles
- Develop more efficient and alternative fuel and storage options, e.g. batteries, fuel cells, hydrogen, biofuels
- Derive technical solutions to increase car-sharing and active travel

Q2: How do we develop transport infrastructure and the transportation system to deliver integrated connectivity?

To address this question, we must:

- Have a systemic understanding of the social, behavioural, cultural, environmental and economic drivers behind people's transport decisions, expectations and demand (bridge gap- to include social and environmental sciences) (links to Q3);
- Develop local and regional infrastructure for transport systems, including more effective technology, communications and a balanced approach to urban planning (i.e. the allocation of space to the different modes, including walking, cycling, public transport, cars and to facilitate freight movements);
- Establish a pathway to ensure the transition to transport systems that utilise increased levels of autonomy is realisable;
- Quantify the impacts of transport on the environment, society and life, and integrated policies (from Q1) that encourage greater sustainability, accessibility and more focus on quality of life and environmental welfare;
- Develop better transport systems and technologies (including apps, such as mobility-as-a-service-type apps) that provide better information to end users across all transport options and integrate this with the average/whole-life cost of these options
- Establish a cross-/multi-disciplinary funding mechanism for transport research;
- Develop a large, city-wide testbed to trial and test innovative engineering solutions, particularly infrastructure, across a wide area.

To enable the research, we need

- An integrated and wider transport strategy
- Policy and research to recognise the cross-/multidisciplinary nature of transport planning and engineering, and the need to integrate into urban/rural planning, future energy planning and its wider societal, economic and environmental impacts (requires multi-layer, 'system of systems approach')
- Government to recognise the importance of transport and its impacts on the (urban/suburban/rural) environment and people's (social-economic) quality of life
- Balance societal needs and expectations with commercial drivers
- Taxes to be an effective way to steer behaviour, and fund further research
- Provide mechanisms to improve the inter-working between transport planners/engineers and data scientists/technologists, to provide better data to inform transport development
- Provision of better and more accessible information (and engagement with) for people around the cost and environmental impacts of transport, e.g. 'whole life' cost of electric vehicles, average cost of using a car (not just fuel), benefits of walking and cycling on health, environmental impacts of buying food out of season

Potential barriers include

- Lack of wider integrated policies
- Lack of cross-/multidisciplinary funding mechanisms (and potential to fall through the gaps between engineering, social science, environmental and economic research)
- Systems level analysis - it is unbelievably complicated and doesn't fit into traditional research silos
- Lack of data or having too much data - robust, uncertainty informed analysis and optimisation is needed
- Balancing the contentions between the need to travel, and how this develops human knowledge/curiosity/learning, and the environmental impacts of travel, which is largely negative, as well as the consumption due to freight movements

Stakeholder Perspectives

A new approach to infrastructure provision and planning is needed from clients and policymakers at all levels, driven by an economic imperative to achieve pressing aims with limited resources.

Increasingly aspects of system that were being thought of as physical engineering are now becoming digital.

Transportation Systems

Q3: How might engineers contribute to developing equitable and accessible transport systems?

To address this question, we must:

- Better understand the transport needs being addressed as the starting point, through bottom-up as well as top-down engagement with end-user/non-user communities, to help design and deliver appropriate and holistic solutions;
- Encourage and train engineers to be more skilled in a wider-range of disciplines, including behaviour science/human factors, social and environmental science;
- Enable socially-acceptable methods for designing transport options, including both perspectives of users and non-users of transport or related services;
- Obtain accurate, widespread, and continuously updated measurements of social and environmental impacts or potential implications, including for low population density areas;
- Provide low-cost answers for all, but especially the developing world;
- Develop options that can be implemented, either as new technologies or retrofit of older technologies;
- Provide a mechanism for engineers to influence the design of urban as well as rural transportation systems, to provide a more integrated approach to city planning.

To enable the research, we need

- Provision of better guidance for stable policies that enable wider options to be developed.
- Growing awareness of the interconnected nature of transport and its/our impacts on the environment and society
- Policy makers and research councils being open to the idea of limiting the performance of transportation systems to deliver maximum value for all as opposed to higher performance for a few, e.g. current investment is skewed towards development of autonomous and electric vehicles as oppose to cycling and walking (which remains the most popular travel mode)
- A national mechanism (including regulation and policies) that balance the voice of the biggest players in the industry (e.g. transport providers, car manufacturers) with those of the 'end-users', including communities, individuals and harder-to-reach groups
- Local and national (urban and rural) transportation planning to include a mechanism that encourage the co-creation and co-design of future transport systems (and in conjunction with local planning)

Potential barriers include

- Research councils/academic efforts competing with the much higher spending power of commercial companies
- Change in Government Policy changing the basis of what is being examined by researchers,
- Measuring societal and planet level impact is incredibly complex

Stakeholder Perspectives

Future of mobility depends on how we can integrate the network with rail, freight, aviation - and data is a big part of this.

Materials

Accelerate environmentally sustainable and socially responsible creation and utilisation of materials

Q1: How should we enable an economically favourable transition to responsible, sustainable, renewable, circular materials and technologies?

To address this question, we must:

- Understand the present and future value of materials in relation to societal, technical, economic and environmental dimensions;
- Gain knowledge of existing chemicals and materials within industrial markets to anticipate alternatives in future markets;
- Understand materials performance and capabilities;
- Explore new material ecosystem models for use;
- Understand the means of revitalising, requalifying and repurposing materials for extended lifetimes within a circular system;
- Develop production approaches compatible with the above, that are scalable, either through distributed production or centrally (from lab to everywhere);
- Understand existing reuse/remanufacture/recovery examples and their economics/ engineering.

To enable the research, we need

- Clustering of manufacturing, use and recovery technologies
- Connection to the arts and social sciences to understand and incorporate societal drivers into our thinking from the earliest stage
- Strong inter and transdisciplinary links with other themes and policies for enabling meaningful research
- Design for disassembly (un-manufacturing) and recovery (cyclability)
- Models of material performance and capabilities, stochastic and verifiable
- Real world use case examples to validate techniques
- Knowledge of industrial market/chemicals/raw materials scale.
- Understanding existing reuse/remanufacture examples and their economics/ engineering
- Identification of manufacturing intermediates more characteristic of current manufacturing practice - recognise that product manufacturer is often multi-stage

Potential barriers include

- Interdisciplinary links between materials science and manufacturing are not sufficiently innovative and expansive, limiting achievements
- Disconnect in research methodology, outputs and timescales across transdisciplinary research
- Education from primary level up - to ensure society has the understanding to assess and drive for the changes required.
- Getting stuck on a solution path. Is remanufacturing the correct way or do new bio-materials fundamentally alter the calculation?
- Failure to understand the time to commercial exploitation and to anticipate long-term 'future market needs' given the timescale of the climate emergency
- Science lags behind assessed and understood goals from social science / government
- Science often does not work best when focussed on specific targets (blue sky vs applied)
- Feedstock supply scale too low for the manufacturing - failure to put the manufacturing of intermediates near to the supply source

Stakeholder Perspectives

Green and renewable technology, and responsible use of materials are the keys to sustainability.

Techniques for the identification and mapping of UK resources and assessment of ease of extraction will be required and need for processing capability in the UK to save materials being sent overseas and returned, reducing the need for UK value chains to rely on overseas partners.

Materials

Q2: How should we replace 'virgin' fossil and rare/ toxic/ mined materials with responsible, sustainable, renewable, circular materials?

To address this question, we must:

- Implement recycling and design for disassembly and recovery, understanding the impacts of recycling on the environment;
- Develop new bespoke materials that could be bio-derived, bio-inspired, multi-functional and self-healing (materials), with feasible growth/synthesis and end-of-life options;
- Understand the impacts and use-cases for 'new' mined resources, and discover sustainable mining practices for them;
- Reduce our addiction to rare or 'difficult to cleanly extract' elements;
- Understand and react to vulnerabilities in our material supply chains by working towards use of abundant elements and adopting resilient design approaches city planning.

To enable the research, we need

- Dialogue with industry to understand models of supply chains, transport systems to feed manufacturing clusters and to distribute products and major end of life issues.
- Means of solving the problem without creating a new one – prediction modelling and decision tools to make holistic supply chain decisions, taking into account existing lab data and extrapolating
- Demonstration of economic benefit from small scale case studies to industry
- Local manufacturing in a global supply chain
- Robotic tools and AI for high throughput experiments and fast optimisation for the models above
- Reliable and dynamic Life Cycle Analysis (LCA) databases and tools and modelling
- Engagement of design researchers and social scientists to help understand how the materials we plan to manufacture will be accepted or introduce unintended consequences
- Open science approach to materials redistribution
- Identification of a clear policy driver associated with 'sustainable materials' that will drive innovation and support new markets

Potential barriers include

- Addressing the scale gap between lab work and manufacturing at scale
- Balancing costs, money and time - what is the lag between intent and implementation - can this be supported
- Reliable Life Cycle Analysis (data and modelling) to ensure sustainable development
- An assessment of what resources are available to use (including biowaste), resource tracking and labelling
- Raw materials precursors and addressing reproducibility
- Competing demand for the same raw materials - e.g. bio and rare metals from use of bio for fuel/ energy/food or rare metals for batteries
- Confused messaging - complex inter- linked issues may get boiled down to carbon
- Global geopolitical situation on rare/toxic materials resourcing and access to materials
- Failure to ensure that new manufacturing processes can compete with (or work with) older established ones whilst they are still being developed

Stakeholder Perspectives

The social and environmental impact of critical raw materials including rare earth metals, which can potentially become scarce, needs attention.

Producing electric batteries and motors with a lower material requirement and overall environmental footprint will be important.

Q3: How can we disrupt pathway dependencies in materials design and manufacturing to meet future market demand for radically more sustainable products?

To address this question, we must:

- Expedite translation from lab to reliably and reproducibly manufacture at appropriate 'scale' - including developing associated enabling technologies, remote quality assurance, process analytics, machine learning, digital twins, federated learning etc.
- Obtain the capacity to dynamically cluster related services for distributed micro-manufacture to create mutually supporting and beneficial outcomes locally and globally that are resilient and responsive to "shock";
- Understand that the materials we have are assets to be used and recycled repeatedly, if economical;
- Understand the new and emerging sectors relating to circularity and sustainability as an expansion of current practices.

To enable the research, we need

- Materials Informatics - data centric Materials Science, AI and Machine Learning (ML) in its widest sense (sourcing to recycling and reusing) coupled with high throughput materials discovery
- Active sensing and use of Edge AI models and federated (or other distributed secure) learning
- Models as assistive tools for decision making during design, research and development stages
- Local and flexible supply chains
- Waste and urban mining to gain value from scrap (for certain materials) - reclassifying scrap as a strategic resource
- Material Tracking methodologies - perhaps related to new business models
- Economic incentives to create local supply chains
- To treat materials as finite resources
- Skills - availability of training from Apprenticeship to re-skilling and upskilling to enable this transition
- Fundamental rework of design practise from solo to embedded group endeavour where new methods of complex interdisciplinary collaboration is essential.
- Major new biomass sources such as terrestrially-generated, underground or in-containers with LED lighting etc
- Carbon neutral and plentiful energy generation enables whole new use cases for reprocessing and material development

Potential barriers include

- Societal concerns (and industry reluctance to take risk) can reject novel products, processes and materials
- Failure to establish international relationships that will ensure the scale of supply chains required
- Challenges and pathways exist outside of areas where we have meaningful control or ability to influence.
- Initial investment for new materials, design and processes can be costly
- Resource scarcity may lock in behaviours - continuing to do what we always did will mean that we get what we always got as a result.
- In a growing population we must use less, not just less per unit of construction
- The radical change required in societal and consumer attitudes to ownership is extremely challenging.
- Limited nutrient supplies for increased biomass generation in UK and globally

Stakeholder Perspectives

There are a lot of new materials and technologies but there is limited trust in available material. This is a bottleneck for innovation, so finding ways to test, assure and validate is important.

Packaging (and other fibre sectors) offers many opportunities (e.g., food, medical, valuable equipment) where it is important to consider sustainable materials selection and design/use, incorporation and use of bio-materials and compostable materials.

Health and Wellbeing

Improve **whole-life health and wellbeing** by developing sustainable, inclusive, and resilient healthcare systems and technologies

Q1: How should we provide an inclusive approach for the development of healthcare solutions throughout our lives?

To address this question, we must:

- Engineer improved healthcare solutions that exploit technology convergence and advances across different disciplines;
- Develop better models of the system from the whole healthcare system to the individual patient to simulate current and predict/optimise future needs and interventions;
- Develop smart systems (including AI) to sift data (including that of patients), identify what is needed and then reduce the need for future data collection;
- Employ inclusive user-centred design and co-design embedded within the development of healthcare solutions;
- Establish uncertainty-based simulation frameworks and tools that could incorporate the effect of epistemic uncertainty, life-course uncertainty, life-style changes, practitioner variability, etc.
- Develop personalised models (including co-morbidities) that can predict the outcomes of new healthcare solutions from personal digital twins to population models;
- Personalise medicine that copes when somebody falls out of the system and needs personal intervention;
- Establish routes for pushing technologies and modelling methods across 'valleys of death' to the point of clinical adoption.

To enable the research, we need

- Larger staged funding programmes for multidisciplinary or translational research with renewal and follow-on opportunities to enable clinical adoption and industry up-take.
- Reverse translation (i.e., new research questions driven by real-world evidence) requires support for prototyping, tooling, piloting.
- Allow for refinement based on reviewer's feedback. Alike NIH grants
- A pipeline of multidisciplinary experts with interest in health from undergraduate to masters to PhD

Potential barriers include

- Difficult to obtain sustained funding at the translational/applied level, and for multidisciplinary working
- Support the link with industry that could develop the research up the TRLs
- Lack of funding to support the development of tools and methods
- Difficulties with NHS being too busy to engage with University research

Stakeholder Perspectives
Engineering will also be important to improve healthcare in ways that are faster, more efficient and more equitable, through technologies such as advanced health informatics and innovations for personalised medicine.

Q2: How might we re-engineer complex healthcare systems for resilience and sustainability?

To address this question, we must:

- Be sustainable and reduce waste in healthcare (including the built environment) and make medical devices reusable and circular and consider all energy cost. Aim to enable a net-zero healthcare system;
- Unpack (everyday and crisis) resilience for healthcare, integrated systems for self-health management, consider whole-supply chain (including workforce);
- Find ways to generate manageable but meaningful models of the whole health care system, including key minimum data required and lessons learned mechanism;
- Account for the specific circumstances in which an intervention takes place (NHS, social services, private, international);
- Share best practice across different systems and put effective change management in place;
- Develop anonymised patient data with the patient controlling access and sharing of their data;
- Have anonymisation and representation standards to enable wide data sharing.

To enable the research, we need

- Funding for fundamental research on modelling
- Clear definitions, exploration of sustainability and resilience in the context of healthcare
- Increased flexibility in the regulatory procedures to increase the use of novel, more sustainable materials in a safe, appropriate manner
- To address the lack of resilience in times of crises, affecting importance placed on environmental impact of material
- To enhance transparency and ensure policy is separated from politics

Potential barriers include

- Lack of resilience in times of crises, affecting importance placed on environmental impact of material
- Economic costs to reduce waste within the NHS
- Short term goals counteracting the time it takes for systematic change to take place

Stakeholder Perspectives
There are many issues in the healthcare field that relate to climate change and sustainability such as the ability to remanufacture medical equipment (as opposed to single-use devices), recycle, reuse and repurpose materials, equipment and technologies or sustainably delivering drugs to remote locations around the world (e.g. potentially using drones).

Health and Wellbeing

Q3: How might we develop novel solutions for inclusive, lifelong wellbeing?

To address this question, we must:

- Have more investment into predictive systems that allow for detecting issues before they arise i.e. preventative medicine (in order to create future prevention programs and empower users to take care of their own health);
- Use technology to support general learning about well-being to empower people to take ownership of their wellbeing;
- Develop wearable and assisted living technologies with data management system;
- Widen the network of information and communication to identify patients needs in order to produce clinical benefit (e.g. tissue engineering); roadmap what is required and what is translatable;
- Embed appropriate knowledge of the developed therapies and interventions within the relevant disciplines and patient populations;
- Develop (human and technological) systems to enable patients to take ownership, helping them with technology to answer questions;
- Instil medical literacy in the general populations through design of our systems.

To enable the research, we need

- To train more data scientists with an understanding of the health system
- Clear policies and legislation about data sharing for users and healthcare systems
- Specific training of medical students and GPs to patient healthcare self-management

Potential barriers include

- Strategic funding to ensure the whole skills pipeline is future-proofed (Masters courses through PhDs through postdocs, etc)
- Siloes of communication and networking (e.g. clinicians and researchers needing to increase knowledge of other disciplines and being allowed to talk to each other)

Stakeholder Perspectives

Human well-being is linked with growth and using resources. Engineering has a role to play in breaking that dependence on the current model of economic development, which currently means that wellbeing of people is linked to constant use and depletion of resources. Also need to create welcoming environments that make people feel safe and pay attention on mental health.

Cross-disciplinary research, particularly in biomedical engineering, is needed, particularly experience and communication from the clinician side.

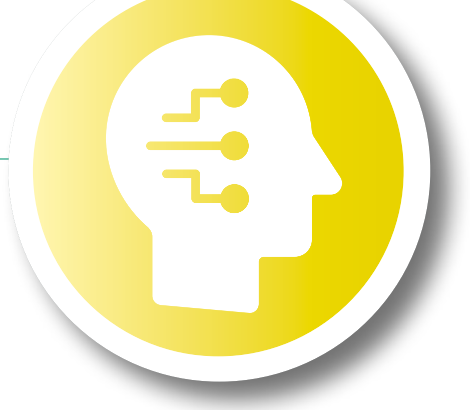
Robotics and AI

Co-design and embed **robotics and AI** into engineering while ensuring ethical use with transparent and equitable decision making.

Q1: How can we certify algorithms and systems to make Robotics and AI autonomous decision-making processes transparent?

To address this question, we must:

- Understand the shifting of responsibility from human to machine decision makers (transparency surrounding algorithms);
  - Use living labs in the real world to understand acceptability and human inclusion and understand the socio-technical boundaries;
- Identify applications and use cases, or classes thereof, that can be safely matched against specific methodologies for autonomous decision making or augmented decision making;
- Ensure appropriate levels of complexity in decision making can be delivered in a timely manner with sufficient robustness to allow real world deployment;
- Establish safe proving grounds to develop complex decision making technology and living labs to prove that technology in real world scenarios;
- Establish methodologies for tracing and analysing complex autonomous and augmented decision making processes;
- Build tools for the derivation of best practice knowledge based on the assessment of failures that leads to improved methods and technologies. e.g.
  - Accurate physics-based and validated models;
  - Modelling the consequences of subsequent decisions;
  - Modelling of complex disturbances, including intentional sabotage (e.g. cyber-attacks);
  - Testing systems of sufficient scale and time (growing number of states), and understand when information becomes non-informative;
  - Being able to capture systems evolution;
- Establish proving grounds and living labs;
  - Shareability of data and models (data standardisation);
  - Representative case studies across disciplines;
  - Good access to data and their interpretation;
  - Multidisciplinary approaches linking experiments, data and models;
  - Human variability and cultural variability in the assessment of acceptability and the decision "boundary";
  - The machine-based perceptual awareness needed to make complex "human type" decisions;
  - Communication of sufficient and timely information.
- Build in learning from failure of methods and systems.



Robotics and AI

To enable the research, we need

- Clear models for the applicability of different validation/certification strategies to different types of decision
- A common ontology of decision making to frame research and application.
- AI models that embed the laws of physics
- Certification metrics that are understood and expose positive or negative bias
- Understanding of dataset design
- Explaining/visualisation of decision-making process to users
- Appropriate Regulation
- Human understandable decision description

Potential barriers include

- Human variability and cultural variability in the assessment of acceptability and the decision "boundary".
- The machine based perceptual awareness needed to make complex "human type" decisions.
- Communication of sufficient and timely information

Stakeholder Perspectives

AI software still needs quality control to ensure there are no bugs, but it might not be rule based and it might operate in complex environments where it is not possible to test how the software will react in all situations. Confidence is needed that the AI will be able to cope with such outlying situations but defining what is needed to ensure safety should be risk based and defining what controls are necessary for different levels of risk is a pressing research question.

Q2: How should we characterise the influence of Robotics and AI on human decision making and behaviour, particularly where this relates to ethical and equitable use?

To address this question, we must:

- Recognise the impact engineering has on people and society at large
  - Look historically at where things went wrong and consider counterfactual scenarios;
  - Look at timeline of impact from immediate to decadal (envisaged primary consequence to often unintended, unforeseen secondary consequence);
  - Consider engineering scenarios to identify those with positive impacts;
  - Involve diverse users and their engagement throughout the design process (even in building scenarios and functional requirements of systems to be designed).
- Understand how people view the decisions made by Robotics and AI (RAI) and why they hold those viewpoints;
  - Transparency in understanding how to effectively indicate ethical concerns to RAI - bias in an algorithm is not necessarily bad, but we need to know what the bias is for decisions to be ethical;
  - Understand how thresholds for accepting algorithmic advice depend on decision consequence (pizza topping vs. voting for governments vs. providing diagnosis/therapy).
- Identify where the shift of responsibility can safely occur in each application;
  - Perspectives for end users (e.g. driverless car driver);
  - Perspectives for developers and expert users (e.g. car manufacturer who installed AI driver, or programmer who used a AI code library as distinct from the person who developed/ conditioned the AI);
  - Understand the risk consequence with respect to the decision making.
- Embed methodologies for co-design and development with users especially where complex ethical concerns exist, for example with elderly or vulnerable users or with children;
- Understand physical and social human machine interaction and its limitations; e.g. at small scale with co-bots or at large scale with systems of smart machines;
  - Build demonstrators to explain use and usefulness of technology and to raise awareness and assess acceptability.
- Understand how real world constraints such as energy, hardware capability, sensing and interpretation limits, constrain the capacity for RAI to benefit humans.

Robotics and AI

To enable the research, we need

- Multidisciplinary research, to bring knowledge and expertise from different areas and provide a vehicle to interact as a community (must find a common ground and language while trusting individual expertise)
- Ability to learn from complex systems design
- Educate researchers in negotiation as an enabler for multidisciplinary research
- Build and invest in underlying skill set base
- Protect individuality, but ensure focused expertise benefits through multidisciplinary initiatives
- Communicate effectively in more diverse teams (e.g. engineers, philosophers, historians, law/ policy-makers)
- A well-considered set of questions/scenarios to focus the community
- Long-tailed funding or mechanisms to enable proactive project clustering or costed extensions.

Potential barriers include

- Dissemination and communication of transdisciplinary science.
- Educational structures that identify the right time to expose people to other disciplines
- Lack of focussed work to support fundamental breakthroughs
- Pyramidal specialisation across education (GCSE to A-Level to Degree)
- Ability to work on big picture questions without the sustained long-term resources to support them.
- Commercial or ethical aspects limit the reach of AI - often consideration about profit win over democratisation processes
- International dimension of AI must be captured. (There will only be effective AI and ineffective AI so how does regulation disadvantage/advantage some countries).
- Availability of data used to train/validate machine learning/AI algorithms (data may be include elements of confidentiality/ownership)

Stakeholder Perspectives

Understand use of robotics and human interaction with machines.

Rapid change by digitisation, convergence of technologies and automation robotics

Robotics and AI

Q3: How should we ensure Robotics and AI are directed to address challenges related to our quality of life, such as the sustainability of resources and the development of resilience.

To address this question, we must:

- Build methodologies for whole life cycle design that consider post-life use and material recovery as well as in-life function and resilience; for example part failures, repairability, energy use, recyclability, part and material reuse all have an impact on sustainability;
- Develop an understanding of the impact of AI and Robotics on national resilience to exogenous shocks and systemic failures that enables investment to improve resilience;
- Develop a regulatory environment that promotes sustainability and resilience in systems and services that impact on our quality of life;
- Educate engineers to understand the importance of sustainability and to question and assess their role in delivering resilience, particularly by enabling them to develop a holistic view of the systems and services they create;
- Understand the capability gains and their limits across sectors;
  - Enabling awareness of automated decisions and processes happening elsewhere at an appropriate level (information overload);
  - Understand how AI is used ethically to improve design tools (from new materials to system processes);
  - Use of AI for data fusion from different sources and build better databases;
  - Understand the limitations imposed by sector specific hardware limitations on RAI systems (supercomputer vs. mobile phones and embedded sensors);
- Co-create and co-design with end users and communities particularly those directly affected by resource and resilience issues;
  - Bounding expectation and capability overpromise;
  - Preparing people for new RAI embedded workflows;
  - Demystifying the role of AI and fears of human disempowerment.
- Understand the human impact of the deployment of RAI;
  - Methods to achieve equitable impact.
- To assess and develop characterisations of AI and robotics systems such that old and obsolete systems that might pose a threat to resilience can be removed from service;
- Retire RAI systems beyond service life considering the inaccessibility of the environments they can end up in (in human bodies, pristine environments, or deep-embedded into user devices that are no longer managed).

To enable the research, we need

- Understanding the different shelf-life of hardware, software and how things like certification (see Q1) is needed to make sure algorithm updates are fit for purpose.

Potential barriers include

- Retiring an AI from a system is also important.
- How can we ensure an AI that is found to have issues after distribution (potentially giving an unfair advantage) gets properly retired once devices are out of factories and in peoples home and remote locations which may well be unknown.

Stakeholder Perspectives
Relevant challenges are cyber-physical Infrastructure, Digital twins, control systems and, robotics and automation in the agricultural sector.

Responsible Engineering

Foster **socially and environmentally responsible approaches to engineering** guided by our understanding of human behaviours and needs.

Q1. How can engineering account for, integrate and continually influence the social, economic and policy factors required to achieve sustainable, resilient and liveable systems?

To address this question, we must:

- Ensure that engineers understand the breadth of questions that need to be asked by engaging across the breadth of cultures, ethnicities and communities;
- Build forums for longitudinal engagement - it is 'how we engage' and well as 'with whom we have engaged';
- Ensure we engage across all fields of engineering and science, society and particularly policy-making taking a transdisciplinary and systemic approach to understanding and addressing challenges;
- Develop a cohort of Social Scientists trained to work reciprocally with Engineers (and vice-versa) to help define the problems and create engineering solutions that are constructed upon and embedded in the needs of society;
- Embrace the idea that engineering is a set of processes and practices that we all do everyday (everyone is an engineer!);
- Understand the societal impacts of engineering decisions, starting by both growing our systemic understanding of the problem space and using people with lived experiences in 'defining the problem', and then playing this out across the conception, design, implementation and operationalising of the new systems;
- Develop research that will identify the key issues where engineering meets society, to ensure we are providing clear and consistent pathways.
  - e.g. Lead on addressing climate change in a manner that creates solutions to re-engineer societal support systems.
  - e.g. Reframe the cyber challenge as more nuanced than air gapping ('air gapping' is a network security measure to ensure that a secure computer network is physically isolated from unsecure networks such as the public internet)
- Grow the engineering research and engineering design methods toolkit with methods that might help engineers design with society and the environment at the core.

To enable the research, we need

- A new paradigm of datacentric systemically founded research that respects privacy
- Engineering-aware and engaged social, environmental, life and other scientists
- Social science-aware and engaged engineers
- Well understood and disseminated mixed methods and tool sets (including research software) shared by contributing disciplines
- A cohort of peer reviewers that are able to handle multi- and trans-disciplinary research and the training to increase the numbers of peer reviewers
- Conception and use of the term 'system intervention'

Potential barriers include

- Access to data and information to support development of new tools and insights
- Researchers from all backgrounds failing to realise that they are engineers - they define and solve problems via ingenuity (the root of the word engineering)
- Lack of multidisciplinary or transdisciplinary peer-review processes
- Lack of capacity building or support for multidisciplinary or transdisciplinary pathways/ careers at all career stages

Stakeholder Perspectives

Engineering research needs to always serve a purpose and contribute towards societal benefit, which requires bringing disciplines together, including economists and policy makers, to address complex problems, as well as more collaboration between academia and industry. Alongside there is a need for standardisation of terminology, especially in emerging fields, to ensure research is reproducible and progress accelerated.

Responsible Engineering

Q2: How can we model, understand, and integrate data from increasingly complex and interconnected systems to help shape our solutions?

To address this question, we must:

- Learn from and build upon the wider community developed (through Q1) to ensure a rooting into transdisciplinary approaches;
- Develop a suite of scenarios that reflect future possible and potential worlds (and the tools to test scenarios). These scenarios need to include key drivers of societal and environmental change and their potential impacts upon patterns of migration and supply chains;
- Leverage novel methods, emerging technologies and modelling across length-scales to explore and define the engineering responses and opportunities within the scenarios;
- Develop the methods by which "data needs" can be gauged to lead to evidence throughout the process of design-implementation-use of technological interventions;
- Close the gaps in our ability to generate data against our ability to intelligently process it, and in contrast to the ability to ethically use the outcomes of mining data in the context of engineered systems;
- Learn how to gain global understanding from data that is mixed quantitative and qualitative, or is varying in temporal and geographical scales and has unverified provenance;
- Understanding data acquisition, processing and knowledge generation tools.

To enable the research, we need

- To encourage large picture thinking and design in general - so that data emerging even from niche research can be ultimately used in systems of systems
- To provide well specified "challenge scenarios" and gather momentum/ produce collaborative approach to developing solutions
- To mandate open research and open data

Potential barriers include

- Continuing to develop data sets that are closed or piecemeal and that cannot be used in systems of systems modelling

Stakeholder Perspectives
In our wider Engineering community we need people who can understand and navigate data science, and use AI and machine learning needs to focus on helping us understand the data we already have.

Responsible Engineering

Q3: How can we develop new engineering science approaches that consistently produce solutions which consider costs and benefits at a society level instead of a technology level alone?

To address this question, we must:

- Pursue the idea of "place" (regions, cities, towns, villages and the peri-urban and rural spaces between them) as multi-dimensional multi-scale systems of systems;
- Create a sufficient understanding of the underlying systems, their interdependencies, structures and dynamics. This implies a focus on data gathering, assimilation and re-thinking how research on such complex challenges should be done in a world of exabyte scale data sets, and then bringing systems into alignment;
- Understand that the urban metabolism (flow of resources, goods, and people in cities) involves a synthesis of systems, some of which will benefit from AI and machine learning, and some of which would be well-served by robotics, while all of which require sympathetic and synergistic systems of governance. Their integration (i.e., the systems themselves and their integration with AI, machine learning and robotics) needs to be explored;
- Take a long-term view in order to acknowledge the need to build up the understanding, generate the data and develop the methods to uncover the underlying structures and behaviours of the natural and anthropogenic systems that support society;
- Understand how we might redefine, reconfigure, foster and take full advantage of ecosystem service provision - of the ground, green, aqueous and atmospheric environments. This is a case for engineering to augment what natural systems supply, understand how these systems interrelate and interact with systems developed by humanity, and to protect and enhance the ecosystem services as we engineer;
- Understand the value, in terms of sustainability and resilience, of engineered solutions. For example, we bury things to protect them, but not electricity cables (which we put in the air, and trees bring them down in high winds) "because it costs too much". The value (in terms of resilience, and sustainability) of burial is very considerable indeed. This requires novel 'business models' - balancing all positive against all negative outcomes, and iteration to improve the positive outcomes

To enable the research, we need

- Systems science and engineering
- Data, and methods to extract meaning from the data (e.g. a library of AI and machine learning methods)
- Climate change mitigation - this plays into our broad sustainability and resilience 'design brief' for our systems-of-systems approaches to engineering research
- To develop clear synergies between circular economic models, industrial ecology, systems science and ecosystems through design thinking.
- Participatory research approaches with diverse groups/communities

Potential barriers include

- Clarity on scope
- Data collection (system structures and dynamics)
- Distributed nature of benefits
- Appropriate funding mechanisms to allow trans-UKRI collaboration
- Evidence at scale that these methods and approaches work.
- Peer review systems that contain narrow and deep peers that appreciate specialist solutions but also appreciate the broader systems approaches

Stakeholder Perspectives

Engineering is not anymore confined to "science of artifacts", rather placed at the crossroads of "science of nature" and "science of human" - this line of thought can be captured in "Engineering in society and engineering for society".

Nature-Based Engineering

Unlock the full potential of **nature-based engineering**

Q1: How should we generate data applicable to a range of specific contexts and use it at the various stages in the design and application of nature inspired or derived technologies?

To address this question, we must:

- Integrate between disciplines to understand circular whole-life impact of nature- inspired engineered systems (e.g. end-to-end usage of carbon and other resources).
- Derive methods to explore and characterise potential unexpected; environmental/social/economic impacts and side-effects of emerging technologies.
- Mitigate methods to address unexpected consequences (biological or resource-based);
- Develop full life-cycle engineering design and analysis tools to weigh disparate factors (performance, economic, risk, sustainability, social) during the design and implementation process;
- Develop model test-beds and ecosystems to allow us to scale-up and assess the long-term compatibility, longevity, and impact of future technologies when translated from the laboratory into the natural environment;
- Characterise and model natural/biological engineering systems by using quantitative and model-based approaches to understand function and impact (e.g. full life-cycle analysis) including comparison with traditional methods (e.g. weighing up natural vs synthetic materials or fuel sources);
- Establish methods that address unexpected consequences and impact (biological or resource-based) of engineering upon nature;
- Build design tools and testing paradigms to understand how living biotechnologies and materials may change (e.g. mutate) beyond their expected function in applications, and how nature evolves to use and capitalise on all available resources.

To enable the research, we need

- Development of methods (both theory/data based and experimental/practical) to predict/quantify primary and secondary impacts/outcomes of nature inspired and derived solutions.
- Methods to monitor/control/enhance the performance of nature-based technologies when deployed in applications.
- Foundational research into the longevity/potential failure modes (e.g. an engineered species mutating or being outcompeted by other species) of nature inspired/derived technologies when exposed to complex real-world environments beyond the laboratory
- Interdisciplinary research and methods that links foundational engineering with understanding/modelling of economic/social/environmental systems over the long-term.

Potential barriers include

- Lack of clear funding paths and remit for nature-based research.
- Need for environmental in situ “test beds” and accessible datasets to validate and build confidence in nature-based technologies and their long-term viability/impact (see Q2).
- Build societal engagement/interest in nature-based technology and (continue) to develop trust/acceptance and legislative support for e.g. genetic engineering, river re-meandering, and other technologies.
- Lack of transparent analysis and reporting methods across industries/sectors to allow accurate comparison and weighing up of different technologies (e.g. in terms of environmental/social/economic impact).

Stakeholder Perspectives
There is a need for digital simulation to speed up testing.

Nature-Based Engineering

Q2: How might we accelerate the lifecycles of natural materials and systems to prioritise and accelerate development and adoption?

To address this question, we must:

- Undertake foundational research and technology development in Materials science, Engineering Biology, Ecology/sustainability, and Biotechnology more broadly;
- Deconstruct science/engineering behind natural/biological systems or processes - thereby advancing our biophysical understanding of how natural systems are encoded, built, and function;
- Generate feedback between adoption, development (e.g. identify social, resource, economic uptake barriers), and technology end-of-life (deconstruction and reuse);
- Build and make available examples/case studies/success stories, for example as an "inspiration" library of science/engineering behind natural/biological systems.

To enable the research, we need

- Clear ownership and definition of nature-based engineering (e.g. by EPSRC) to support clear funding routes. Potentially also longer-term funding horizons giving time to deploy and assess long-term impact of technologies on nature.
- Connecting the inherently interdisciplinary community to build an "inspiration" library. Share examples, case studies. Also to provide a dataset to compare/contrast benefits/costs of nature vs traditional methods.
- Education - across different levels (general public to UG to senior scientists).
- Support for diverse and large projects to fully realise the potential (diverse in the sense of how nature is used as well as which sectors are included).
- Foundational research and technology development, likely linking work across all councils/industry sectors.

Potential barriers include

- At present there is no clear target and ownership (e.g. disciplines within universities, or funding bodies) for nature based engineering.
- Lack of clarity around what nature-inspired engineering is and what it can potentially achieve/deliver - this hampers its impact and uptake across research/industry.
- Lack of focus on grand challenges and big picture, including (for example) databases of outstanding challenges, opportunities, resources, waste products - opportunities to create circular, resilient industry clusters.
- Separating "effective" approaches from green-washed "natural is always good" thinking.
- Engineered nature-based solutions are often not reliable and can behave unpredictably over long time horizons - we need better means to design for and guarantee long-term performance
- Clear ownership within UKRI of nature-based and nature-inspired engineering

Stakeholder Perspectives
Nature-based solutions, inspired by biology, can be applied to conventional challenges where humans and nature can co-exist.

Nature-Based Engineering

Q3: How might we use biology and nature to move beyond the current materials paradigm and harness these in engineering applications?

To address this question, we must:

- Advance foundational research and understanding in biosciences. For example research into developmental (synthetic) biology to understand how macroscopic biomaterials (e.g. bones or shells) are assembled in nature, and how we might re-purpose these systems for new biotechnologies;
- Learn from nature to develop multi-functional and/or adaptable bio-materials (for example self-healing, forming, deconstructing or living materials);
- Develop methods to better reconstitute, reconfigure or reassemble nature-inspired building blocks for a given engineering function;
- Understand the role of nature-inspired materials and their manufacturing in achieving net-zero lifetime impact and long-term sustainability;
- Develop new technologies for waste management by learning how biology degrades/recycles materials or ingredients/components.

To enable the research, we need

- Science and engineering research supporting foundational technology development that must be achieved as a precursor for subsequent exploitation in Materials applications (e.g. as a precursor we must first understand how nature uses subtle biochemical signalling and regulatory functions to control material production/growth).
- Tools/approaches to tune longevity/robustness/degradation of engineered biomaterials to build their capability as viable long-term replacements for existing materials (e.g. plastics).
- Methods for the modelling, controlled manufacturing, and subsequent dynamic monitoring of all synthetic materials, enabling quality controlled repeatability/reliability in their production, and monitoring/ maintenance when deployed in situ.
- Methods to link biological or nature-inspired designs with traditional materials - for example interfacing engineered biological materials with electronic, metal, computational, plastic components to form hybrid systems.
- Technologies to generate positive impact, or mitigate/offset negative impact, on natural systems more broadly e.g. carbon capture, bioremediation, enhanced biodiversity, new materials recycling approaches from biology/chemistry.

Potential barriers include

- Existing infrastructure, and government subsidisation, makes it difficult for incumbents to disrupt traditional petrochemical/fossil fuel based processes (e.g. plastic manufacturing).
- Currently limited overlap and interdisciplinary work happening that links biotechnologists with fields such as semiconductor manufacturing, materials, and others.
- Access to national/high-end facilities (e.g. synchrotrons) to enable study of material properties, internal structures, etc.
- Relevant skills development for next generation of engineers and scientists, and re-training of existing technical experts to contribute to the field.

Stakeholder Perspectives

There is an important role of engineering in the field of regenerative medicine, where novel biomaterials with very specific formulations are needed.

There can be a shift from sustainable design to restorative/regenerative design.

Global Engineering Solutions

Deliver adaptable **global engineering solutions** that are compatible with our understanding of the planet's ecosystem

Q1: How can we develop resilient systems approaches to ensure resources (food, water and energy supply) are sustainable and equitable for all?

To address this question, we must:

- Adopt a trans-disciplinary approach;
- Better understand society and eco-system needs;
- Understand the existing resources and how they can be used in a sustainable way;
- Maximise existing process efficiencies through new science for sustainable infrastructure;
- Develop new technologies that support sustainable delivery of resources and energy.
- Develop low energy processes for production of water and food;
- Develop a systems of systems approach where increasing resilience does not come at the cost of sustainability;
- Find new, more (sustainable and resilient) vectors for delivery (including ambient sources of energy, food and water);
- Improve connections between systems for better efficiency and equitability;
- Develop digital twins to support improvements in efficiency and equitability.

To enable the research, we need

- Integrated system approaches, including an engineering approach to increase impact.
- New mechanisms for trans-disciplinary research on this theme.
- Transfer and translate existing knowledge between the water, food and energy sectors
- Accurate, global and accessible data that support actionable knowledge.

Potential barriers include

- Wealth-driven demand
- Research with narrow focus on UK plc rather than on a global scale.
- Intrinsic links between energy, food and water adding complexity to the problem.
- Policies and regulations that hinder implementation.
- Lack of in-depth knowledge of existing resources and their possible sustainable reuse.

Stakeholder Perspectives

There is a drive to diversify the foods that are procured by large food companies, and there is an open question on how to grow them sustainably.

Key engineering challenges are regenerative agricultural practices and bringing these through the whole supply chain.

Engineers should be sustainability and socially conscious to provide the solutions for clean air and clean water for all, sustainable food production for a growing population, and equity of resources.

Global Engineering Solutions

Q2: How should we circularise production, storage, and use of resources and energy to ensure end-to-end reusability and recycling?

To address this question, we must:

- Develop a good understanding of how appropriate circularisation is feasible/practicable for different sectors;
- Assess in detail the different needs for recycling/reusing (from large structures to buildings and materials) and types of waste, considering contamination issues;
- Develop scientific breakthroughs to capture and reuse wastes much more efficiently;
- Develop sustainable processes for circularisation of energy, water and food;
- Link better energy, water and land to biomass production to promote circularity;
- Better quantify the recovery of resources, of carbon, nitrogen, phosphorus, potassium and water to promote circularity;
- Use design-based research to promote population habit change;
- Enable sufficient and diverse supply of sustainable energy and water to support vertical agriculture.

To enable the research, we need

- Research into supply chain and traceability of resources and processes.
- A systems approach to understand the unintended consequences of circularisation of water-food-energy.
- Working with the public to improve the public perception of waste including water, food and energy.
- Obtain better data on the scale and spread of waste.

Potential barriers include

- A lack of engineering thinking from high level policy down to individual science.
- Heterogeneous dilute streams of resource recovery.
- Commercial and cultural pressures privileging the new rather than the reuse.

Stakeholder Perspectives

Engineers will be able to advance sustainable practices across sectors (e.g. from manufacturing to agriculture) and mitigate further change and adaptation.

Hydrogen, Fusion and Fission offer exciting opportunities for the future, providing social acceptance is progressed and the cost and security of energy transmission is kept manageable.

Global Engineering Solutions

Q3: How might engineering contribute to reducing and repairing the impact - both past and future - of human activities on the natural environment?

To address this question, we must:

- Understand in detail the planetary impact of our activities and find examples whereby we successfully reverse adverse human impact;
- Design methods and metrics for engineering with nature;
- Develop engineering systems that work with and restore nature globally;
- Research into assessing, conserving and adapting existing infrastructure to maximise the sustainable use of existing resources and energy;
- Develop more advanced approaches to chemical separation for greenhouse gases, including negative emissions, to enable new synthesis processes and resource recovery from other dilute media;
- Use modular process technologies for energy, food and water that allow rapid scale up of new technologies to globally impactful scale.

To enable the research, we need

- To create, through research, investable solutions at small scale, that are readily scalable.
- More assessment and understanding of the current built and natural environments

Potential barriers include

- Poor understanding of built and natural systems, effective interventions and impact.
- Financial pressures on brand/suppliers values to decarbonise.
- Lack of longitudinal support from discovery to impact for an inherently longitudinal problem.

Stakeholder Perspectives

Solving current priorities (e.g Net Zero) will inevitably create more problems and global inconsistencies. Existing problems are just getting bigger as populations expand and infrastructure needs continue to grow.

Efficient delivery of major engineering programmes needs to be done at scale to keep within climate change aspirations.

Skills are an important factor to manage climate change impacts, specifically to understand the just transition and global societal impact of engineering decisions.

ANNEX C:
Summary of the Process

Summary of the Process

The motivation to determine the challenges where engineers and engineering research play a significant role in the next 10-15 years was devised and delivered by the Engineering theme at EPSRC. The approach, to convene the engineering community and related stakeholders to derive a bottom-up, community-driven vision of the future, was agreed following extensive discussion and guidance from EPSRC strategic advisory groups who were consulted.

As an initial task, the EPSRC project team secured two well-respected co-chairs to be the figureheads of the activity: Professor Dame Helen Atkinson DBE FREng and Dr Peter Bonfield OBE FREng. Their role was to provide credible community leadership and strategic direction throughout the process and ultimately suggest the recommendations found in this report.

The priorities, themes and challenges that were identified by the community were obtained through an extensive process of engagement over a nine-month period, shaped by the co-chairs and the EPSRC team. Throughout, the ideas and perspectives from the community evolved, diverged and converged into those presented in this report. A schematic to illustrate this process is shown in figure 3.

A core activity of the whole process was a series of workshops, held virtually on Nov 30th, Dec 1st, Dec 7th and Dec 9th 2021. The workshop's purpose was to provide a vehicle for a diverse representation of the Engineering community to identify and develop the technological challenges within an inclusive, collaborative immersive environment. The four workshops were planned and facilitated by Know Innovation[6], alongside the EPSRC project team and the co-chairs. Support and expert guidance was provided by a steering group of advisors drawn from the EPSRC Engineering Strategic Advisory Team and Engineering Early Career Forum.

EPSRC openly advertised the opportunity to attend these workshops through social media, asking each applicant to provide rationale for attendance. The participants were required to attend all four workshops. In total, 207 applications were received from across the UK. The final group of 51 workshop attendees were selected by the project team and steering group based initially on their rationale for attendance and then to ensure a breadth of representation in career stage and discipline, and across a variety of communities including physical sciences, biological science, environmental science, social science, economics, mathematical sciences, design and architecture. The full list of workshop participants is in Annex D.

As the first stage of the idea generation process, all 207 applicants were asked their views on the most interesting questions that might be addressed by (or within) Engineering in the next 10-15 years. This entire suite of 621 'future perspectives' were considered and refined to inspire the conversations at the workshops themselves (indicated in figure 3). Among the exciting challenges proposed were holographic communications, quantum applications, manufacturing in extreme environments, engineering tools to enhance biodiversity and extra-terrestrial colonisation. A total of 63 of these were pre-selected by the project team and the co-chairs during the sift stage of the process. Before the workshops commenced, the selected workshop participants were tasked to sort these ideas into themes to explore and discuss at the first workshop. These broad 'pre-clusters', in domains such as transportation and space, were reviewed and approved by the co-chairs.

At the first two workshops, small groups of participants explored, added to and refined the broad clusters and converged these into focussed themes. The three priority questions were derived for each theme. This was followed by two further workshops to further progress the themes, where the participants identified the antecedent research, enablers and barriers that would need to be overcome to address the questions which, if answered, might lead to a step-change in the field of engineering.

As illustrated in Figure 3, the workshops encouraged continual divergence and convergence of ideas throughout the process which enabled a rich set of interconnected outputs to emerge. These detailed outputs have been presented as the Technological Challenges within this report.

[6] https://knowinnovation.com/

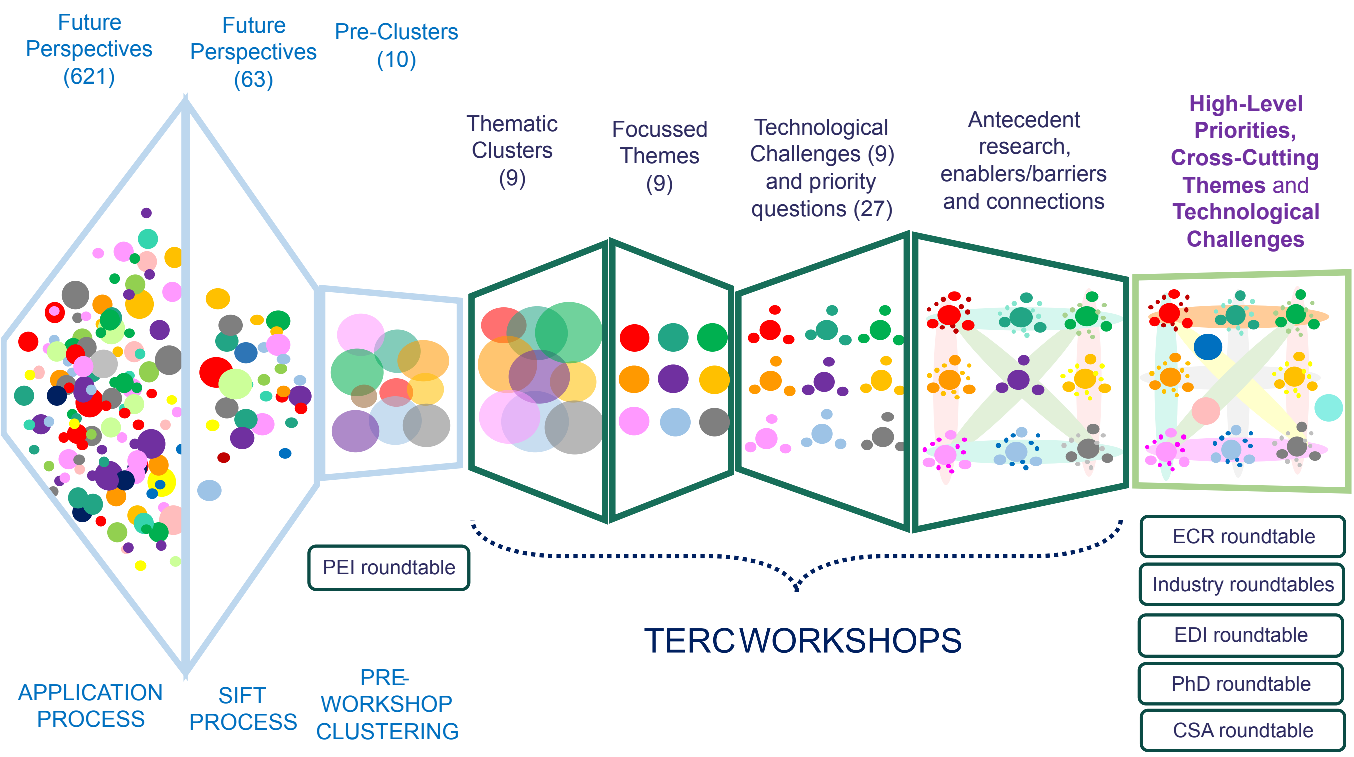


Figure 3: Schematic representation of the flow of ideas throughout the TERC workshop process and sequence of roundtables. The trapeziums indicate the perceived divergence and convergence of ideas. Numbers in brackets indicate the number of ideas, clusters and questions identified.

In parallel with the four workshops, a sequence of virtual roundtable meetings took place to draw in different perspectives from a diverse range of stakeholders including the Royal Academy of Engineering and the major professional engineering institutions, industry, engineering EDI groups, early career researchers, EPSRC-funded PhD students and UK Government chief scientific advisors. The participants from each of the roundtables are listed in Annex E. The content from these roundtables strongly informed the High-Level Priorities and Cross-Cutting Themes that have been identified. Also, this wealth of information has been intermeshed, where appropriate, into each Technological Challenge to provide the necessary cross-over and integration.

The result of this comprehensive and inclusive engagement process has led to a detailed spectrum of challenges, presented in this report. Emerging findings from this initiative have been presented and discussed with the EPSRC Engineering Strategic Advisory Team, EPSRC Science, Engineering and Technology Board and EPSRC Council.

TERC participants

TERC Workshop participants

Gerry Agnew	Director – Hydrogen Accelerator, University of St Andrews
Kirstie Andrews	Senior Lecturer in Engineering Materials and Biomedical Engineering, Manchester Metropolitan University
Steven Banwart	Director of Global Food and Environment Institute, Leadership Chair in Integrated Soil-Agriculture-Water Research, University of Leeds
Richard Bibb	Professor of Medical Applications of Design, Loughborough University
David Bisset	Director, iTechnic Ltd (Engineering SAT member)
Helen Bridle	Associate Professor, Heriot-Watt University
Irene Carra	Lecturer in Chemical Processes, Cranfield University
Lionel Clarke	Chair, UK Engineering Biology Leadership Council
Sandy Cochran	Professor of Ultrasound Materials and Devices, University of Glasgow
Ian Cotton	Professor of High Voltage Technology, University of Manchester
Anthony Croxford	Professor of Ultrasonics and Dynamics, University of Bristol
Daniele Dini	Professor in Tribology and Director of Research Imperial College London
Lorna Dougan	Professor of Physics, University of Leeds
Claudia Eckert	Professor of Design, The Open University
Alex Elliott	Research Fellow, Cranfield University
Fern Elsdon-Baker	UKRI Future Flight Challenge Social Science Research Director/Director Research Institute for STEMM in Culture and Society (ISTEMMiCS), University of Birmingham
Michael Fertleman	Consultant Physician and Visiting Professor, Imperial College London
Alejandro Frangi	Diamond Jubilee Chair in Computational Medicine / RAEng Chair in Emerging Technologies, University of Leeds
Elena Gaura	Professor of Pervasive Computing, Director of the Institute for Mathematical, Physical and Computational Sciences, Coventry University
Kate Goldsworthy	Professor of Circular Design and Innovation, University of the Arts London
Cristina Gonzalez-Longo	Chartered architect and Director of the MSc in Architectural Design for the Conservation of Built Heritage, University of Strathclyde
Alison Halford	Research Fellow, Research Centre for Computational Science and Mathematical Modelling, Coventry University
Kirill Horoshenkov	Professor of Acoustics, University of Sheffield
Alton Horsfall	Professor in Electrical Engineering, University of Durham
Louise Horsfall	Professor of Sustainable Biotechnology, University of Edinburgh
Tanvir Hussain	Professor of Surface Engineering, University of Nottingham
Laurie King	Senior Lecturer in Materials Chemistry, Manchester Metropolitan University
Damien Lacroix	Professor of Mechanobiology, University of Sheffield
Yang Lu	Lecturer in Computer Science, York St John University
Rebecca Lunn	Professor of Engineering Geosciences, University of Strathclyde
Jill MacBryde	Professor in Design, Manufacturing and Engineering Management, University of Strathclyde
Martin Mayfield-Tulip	Professor of Engineering Design, University of Sheffield
Greg Mutch	Royal Academy of Engineering Research Fellow Newcastle University
Siddharth Patwardhan	Professor of Sustainable Chemical and Materials Engineering, University of Sheffield

Karen Robertson	Assistant Professor University of Nottingham
Christopher Rogers	Professor of Geotechnical Engineering and Director of the National Buried Infrastructure Facility, University of Birmingham
Lars Schewe	Lecturer in Operational Research University of Edinburgh
Tim Smithers	Self employed
Emiliano Spezi	Director of Research for Cardiff University School of Engineering., Cardiff University
Harrison Steel	Associate Professor of Engineering Science, University of Oxford
Michael Sulu	Lecturer, Dept of Biochemical Engineering, UCL
Philipp Thies	Associate Professor in Renewable Energy, University of Exeter
Blair Thornton	Professor of Marine Autonomy, University of Southampton
Magda Titirici	Chair in Sustainable Energy Materials/Director of Research, Imperial College London
Iain Todd	Professor of Metallurgy and Materials Processing, University of Sheffield
Prashant Valluri	Professor of Fluid Dynamics, University of Edinburgh (Engineering SAT member)
Nejra van Zalk	Senior Lecturer in Psychology and Human Factors, Imperial College London
Karl Whittle	Professor of Zero Carbon and Nuclear Energy, University of Liverpool
Ruth Wilcox	Professor of Biomedical Engineering University of Leeds
Alan Wong	Research Fellow, University of Southampton
Benjamin Woods	Senior Lecturer in Aerospace Structures, University of Bristol

TERC Workshop Facilitators

Toby Scott	Know Innovation
Emma Skipper	Know Innovation

TERC Workshop Steering Group

Jon Binner	Professor of Ceramic Science and Engineering, University of Birmingham (Outgoing Engineering SAT Chair)
Barbara Shollock	Professor and Head of Department of Engineering, Kings College London; (Incoming Engineering SAT Chair)
Barry Lennox	Professor of Applied Control, University of Manchester (Engineering SAT Member)
Davide Mattia	Professor of Chemical Engineering, University of Bath (Former Engineering SAT Member)
Nicole Metje	Professor of Infrastructure Monitoring, University of Birmingham (Former Member of Early Career Forum)

TERC participants

Stakeholder Roundtable Participants

Royal Academy of Engineering/ Professional Engineering Institutions Roundtable, 29th October 2021

Chaired by Dame Helen Atkinson and Peter Bonfield

Andrew Clark	Director of Programmes, Royal Academy of Engineering (RAEng)
Alicia El Haj	Deputy Chair of the Research Committee, RAEng
Colin Church	CEO, Institute of Materials, Minerals and Mining (IOM3)
Jon Pritchard	CEO, Institution of Chemical Engineers (IChemE)
Sir Julian Young	President, Institution of Engineering and Technology (IET)
Giles Grant	Director Knowledge Services and Solutions, IET
Alice Bunn	CEO, Institution of Mechanical Engineers (IMechE)
Gordon Masterton	Past President, Institute of Civil Engineers (ICE)
Minna Karstunen	Research and Development Enabling Fund Panel Member, ICE
Jonathan Cooper	Past President, Royal Aeronautical Society (RAeroS)
Steph Neave	Head of Research, Engineering UK
Laura Finney	Head of Emerging Technologies, BBSRC (Observer)
Wendy Matcham	Head of Resilient Environment, NERC (Observer)

Early Career Researcher Roundtable, 13th December 2021

Chaired by Peter Bonfield

Irene Carra	Cranfield University
Maria Papathanasiou	Imperial College
Lauren Thomas-Seale	University of Birmingham
Yihua Hu	York University
Antonio Torija Martinez	University of Salford
Ruoyang Yuan	University of Sheffield
Ross Minty	University of Strathclyde
Kirstie Andrews	Manchester Metropolitan University
Will Midgley	Loughborough University (Engineering SAT member)

Equality, Diversity and Inclusion Roundtable, 13th January 2022

Chaired by Peter Bonfield and Dame Helen Atkinson

Alfredo Carpineti	Pride in STEM, Chair and Founder; Science Writer; Astrophysicist
Belinda Colston	University of Lincoln, Director of Eleanor Glanville Centre, Professor in the School of Chemistry
Elena Gaura	Coventry University, Professor of Pervasive Computing; EPSRC champion with the Women's Engineering Society
Elizabeth Donnelly	Women's Engineering Society, CEO
Lucy Williams	University of Nottingham, STEMM-CHANGE Inclusion Matters Project Officer
Mara Makoni	Association for Black and Minority Ethnic Engineers, Corporate Partnerships Lead
Mark McBride-Wright	EqualEngineers, Founder and Managing Director
Michael Sulu	UCL, Lecturer of Biomedical Engineering; Leading Routes, STEM Lead

Robert Adediran	EDI consultant; Royal Academy of Engineering, Senior Manager Diversity and Inclusion
Simonetta Manfredi	Oxford Brookes University, Professor in Equality and Diversity Management and Director of the Centre for Diversity Policy Research and Practice
Susan Krumdieck	Heriot-Watt University, Professor at the School of Energy, Geoscience, Infrastructure and Society
Vanessa Diaz	UCL, Professor of Healthcare Engineering, Vice-Dean for EDI in Engineering Sciences (Engineering SAT Member)

PhD Student Roundtable, 18th January 2022

Chaired by Peter Bonfield and Dame Helen Atkinson

Alex Murray	CDT Gas Turbine Aerodynamics
Anne-Pia Marty	CDT Sensor Technologies for a Healthy and Sustainable Future
Ashley Victoria	CDT Molecules to Product
Ben Luqmani	CDT Engineering for the Water Sector (STREAM IDC)
Daniel Ruth	CDT Water Infrastructure and Resilience
Douglas Morley	CDT Future Infrastructure and Built Environment
Elisabetta Schettino	CDT Advanced Automotive Propulsion Systems
Grzegorz Sochacki	CDT Agri-Food Robotics: AgriFoRwArdS
Hilde Metzger	CDT Future Ultrasonic Engineering
Jennifer Castelino	CDT Fluid Dynamics
Lucy Dougill	CDT Future Innovation in Non-Destructive evaluation
Maria Laura Vieri	CDT Engineered Tissues for Discovery, Industry and Medicine
Miranda Lowther	CDT Future Autonomous Robotic Systems
Rebecca Presswood	CDT Sustainable Infrastructure Systems
Ryan Leeming	CDT Complex Particulate Products and Processes
Simona Della Valle	CDT Synthetic Biology
Sofia Medina Cassillas	CDT Future Propulsion and Power

Industry Roundtable, 31st January 2022

Chaired by Dame Helen Atkinson

Paul Gosling	CTO, Thales UK
Dave Smith	Director of Central Technology , Rolls Royce
Paul Beasley	Head of R&D (UK), Siemens
Mark Bentall	Head of R&T programme, Airbus
Martine Gagné	CTO, Meggitt Plc
David Nesbitt	Director Electrical and System Eng., Jaguar Land Rover
Malcolm Lee	Group Head Innovation and Tech, Babcock International
Simon Weeks	CTO, Aerospace Technology Institute
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Rob Buckingham	Director, UKAEA

TERC participants

Kay Yeong	Principal Technology Scout, Dyson
Julian Cracknell	Chief Technology and Information Officer, BAE Systems
Bryan Allcock	CEO, TRL9
Sumitesh Das	Director of R&D, Tata Steel UK
Mihai Caleap	CEO, Calyo

Industry Roundtable 2 , 15th February 2022

Chaired by Peter Bonfield

Florence Lam	Director, Arup
Gabriel Durojaye	Digital Innovation Leader, Costain
Bill Hewlett	Technical Director, British Board of Agrément
Chrysoula Litina	Principal Research Engineer, National Highways
Eve Germain-Cripps	Head of Process Engineering, Thames Water
Mike Hinton	Consultant R&T Partnerships, High Value Manufacturing Catapult
Tony Quinn	Test and Validation Director, Offshore Renewable Energy Catapult
Helen Meese	CEO, The Care Machine Ltd
Mark Apsey	Managing Director, Ameresco
Jon-Paul Sherlock	Senior Director, Innovative Manufacturing, AstraZeneca
Robert Smith	Director, RCNDE and NDEvR
Kati Gastrow	Global Engineering Manager – Robotics and Automation, Unilever

Chief Scientific Advisors Roundtable (Brown Bag Breakfast), 13th April 2022

Chaired by Dame Angela McLean, CSA MoD and attended by Dame Helen Atkinson and Andy Lawrence

Sir Patrick Vallance	Government Chief Scientific Adviser
Paul Monks	Department for Business, Energy and Industrial Strategy
Osama Rahman	Department for Education
Gideon Henderson	Department for Environment, Food and Rural Affairs
Mike Short	Department for International Trade
Alan Penn	Department for Levelling Up, Housing and Communities
Sarah Sharples	Department for Transport
Robin May	Food Standards Agency
Andrew Curran	Health and Safety Executive
Stephen Belcher	Met Office (EPSRC Council Member)
Dame Angela McLean	Ministry of Defence
Julie Fitzpatrick	Scottish Government
Robert Hoyle	Welsh Government
Alastair Smith	Department of Education

International contributors

Alton D. Romig Jr.	Executive Officer, U.S. National Academy of Engineering
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Low Teck Seng	Chief Executive Officer, National Research Foundation, Singapore
Yuko Harayama	Vice-president, Engineering Academy of Japan
Chris Manzie	Head of Electrical Engineering, University of Melbourne, Australia
Guy Gosselin	Executive Director, Engineering Institute of Canada

EPSRC Project Team

Andy Lawrence	Joint Head of Engineering
Maisie England	Joint Head of Engineering
Lucy Hackett	Senior Portfolio Manager, Engineering
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