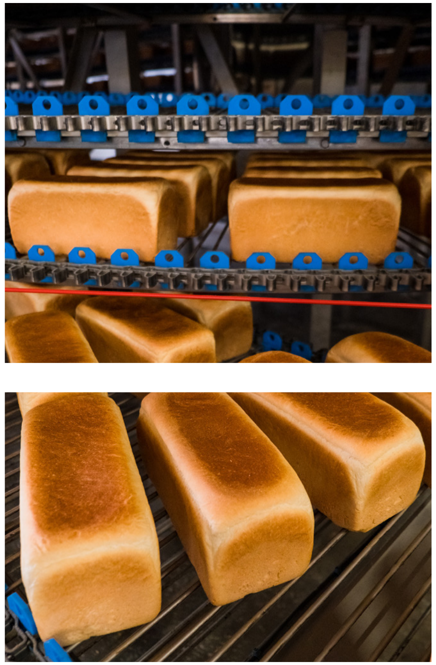
IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

# Chemical Engineering Matters



4th Edition

# Foreword

I'm pleased to introduce the 2022 revision of *Chemical Engineering Matters*.

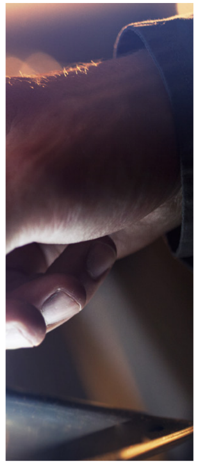
Chemical engineers provide leadership and solutions as our global society faces myriad challenges and opportunities, often interconnected. Challenges include sustainable development, climate change commitments, circular economy development, and access to and security of affordable energy, water, food, and health. Chemical engineers bring science-based expertise, skills in systems, safety, and digitalisation; they work in collaboration with others, globally and locally, to deliver strategy and projects.

*Chemical Engineering Matters* is the technical roadmap of the Institution of Chemical Engineers (IChemE). It offers valuable guidance about the breadth, cross-cutting systems approach, and importance of chemical engineering. It also provides signposts to developing and expanding our discipline in future, and links to the United Nations' Sustainable Development Goals (UN SDGs).

*Chemical Engineering Matters* has been valuable in my own career. Since the publication of the first edition in 2013, it has been an important guide to understanding the breadth of chemical engineering. It really opened my eyes to how central chemical engineering is in achieving a sustainable future and solving major challenges. The document was also a useful signpost to future directions I might explore.

People have told me that they value and use *Chemical Engineering Matters* for a range of purposes, such as:

- engaging with policy makers;
- informing professional career formation;
- guiding learning outcomes in academic curricula;
- provoking curiosity for areas of research and innovation;
- guiding students about future careers; and
- communicating with the public about what chemical engineers do.



I thank everyone involved in this revision and its predecessors. A document like this is only possible because of the thought leadership provided by our learned society groups across the world. I, particularly thank the many chemical engineers and groups within IChemE who volunteered their expertise and input to write this document.

As our world and technology continues to change, this document will evolve with it. I encourage you to read, share and discuss. Let's continue our engagement about how chemical engineering matters.

Alexandra Meldrum

Alexandra Meldrum
Vice President Learned Society, and
Member of the Board of Trustees IChemE

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# Executive summary

## Introduction

*Chemical Engineering Matters* provides a framework for society and stakeholders to explore how chemical engineers are central to addressing our global challenges. It identifies four key challenges and long-range 'vistas' on their development: Water, Energy, Food and Wellbeing, influenced by cross-cutting knowledge and skills in the fundamentals of chemical engineering and also in manufacturing, process safety, multi-disciplinary and collaborative working, and digitalisation, as shown in Figure 1. Sustainability and ethics, values and diversity are all-encompassing principles that underpin efforts in all the areas.

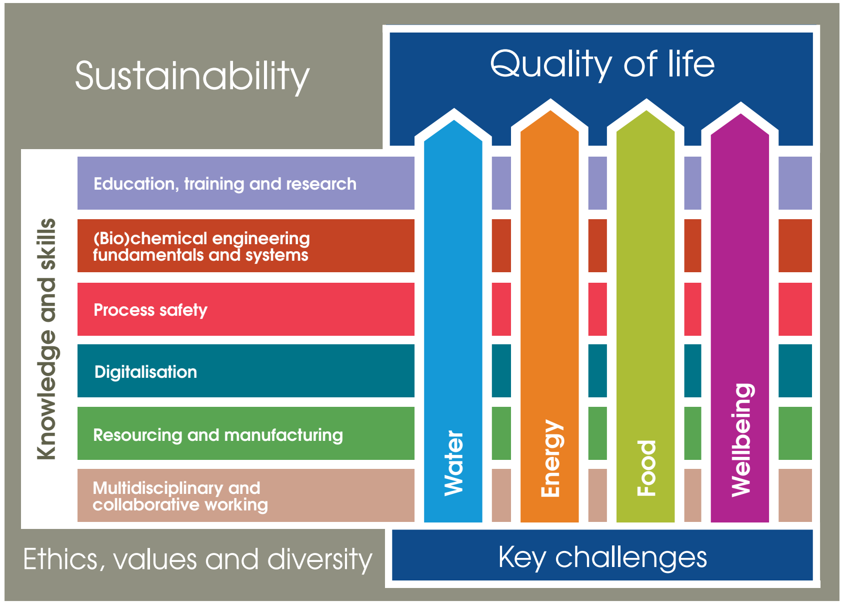



Figure 1. *The Chemical Engineering Matters* Model

SUSTAINABLE DEVELOPMENT GOALS

In recent years, the emergence of the United Nations' Sustainable Development Goals (SDGs) has created a new framework for meeting societal need. This latest version of *Chemical Engineering Matters* re-examines the four challenges through the lens of the SDGs and provides insights into the future roadmap of chemical engineering as showcased through IChemE's centenary project in 2022, *ChemEng Evolution*.

## Ethics, values and diversity

Engineers must operate with the highest ethical standards to protect the wider societal interests. Ethical culture requires self-regulation, taking responsibility of one's actions and raising concerns in the event of an unethical action on the part of others. It also requires a strong commitment from individuals and organisations through initiatives such as regular training and education of chemical engineers.

Equality, diversity, and inclusion (ED&I) ensures fair treatment and opportunity for all. Introducing diversity and inclusion encourages innovation and productivity in an organisation, including chemical engineering organisations. IChemE has an important role to play in supporting ethical conduct, diversity, equality and inclusion within the chemical engineering profession and its different operational sectors.[1] Some recent examples of IChemE's role include requiring ethics education in accredited chemical engineering degree courses, organising training courses, and developing relevant materials in the learned society priority areas, eg ethical use of digitalisation and responsible production.

## Policy, economics and public perception

Recent energy and food crises, coupled with other challenges including climate change, cybersecurity, inflation, and economic uncertainty, are prompting countries to strengthen their policy frameworks and drive economic growth. During uncertain times, chemical engineers can catalyse positive change. Chemical engineers apply practical science-based knowledge, engineering best practice and a collaborative, multidisciplinary approach to develop sustainable solutions. IChemE promotes scientific debate among stakeholders, encourages constructive dialogue with policy makers, and collaborates with the wider science and engineering community to promote the profession and deliver a coherent engineering voice on technical policy.

## Safety and risk

Managing safety and risk is fundamental to chemical engineering. Accidents at highly hazardous facilities may be rare but can have serious and devastating effects, thus requiring a rigorous approach to process safety and loss prevention. The IChemE Safety Centre (ISC), launched in 2014, brings together operators, service regulators and academics to collaborate and exchange ideas towards delivering best practice in process safety.[2] Through collaboration, IChemE is working with others across sectors and disciplines to develop a common approach to risk management, considering process risks, as well as uncertainties stemming from our changing environment.

## Education, training and skills, research and innovation

IChemE upholds standards and supports a common approach by accrediting hundreds of higher education programmes around the world, offering professional registration and promoting training through accredited company training schemes and its own portfolio of courses. IChemE supports chemical engineering education development through its academic journal, *Education for Chemical Engineers*, and showcases latest advances in chemical engineering through its magazine, *The Chemical Engineer (TCE)* and its extensive portfolio of journals. The *Sustainability Hub* provides training courses to upskill engineers,[3] and the *Knowledge Hub* provides access to thousands of peer-reviewed resources.[4]

Research and innovation in chemical engineering aims to address some of the world's most complex challenges including climate change, energy, food and water, bioeconomy, health and biotechnology, and industry digitalisation. Chemical engineering is evolving rapidly and new applications such as molecular modelling, quantum chemistry and synthetic biology are emerging. Chemical engineers bring a strong understanding of both systems and processes, thus contributing hugely to multidisciplinary research through a fresh perspective. IChemE has an important role to play as a link between researchers, funding bodies and industry to promote research and innovation in chemical engineering.

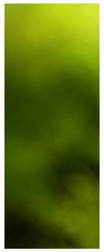
## Water

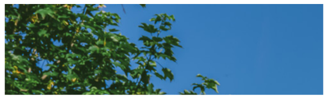
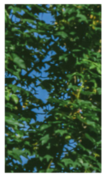
Chemical engineers have successfully managed both potable and wastewater. However, because of climate change, population growth, industrialisation, and agricultural demands, access to clean water for human consumption (drinking and cooking) is under increased pressure. Chemical engineers play a significant role in treatment and supply of potable water, improving the efficiency of industrial and communal water supply, and wastewater recycling, with recovery of valuable materials such as metals, nitrates, phosphates and biogas contributing to the overall system sustainability. They are involved in wastewater treatment technology development and integration of water and energy industries, such as through electricity generation from co-digestion of sewage, industrial effluent, and domestic waste. Wastewater and low-grade heat from the powerplants may also be used for electricity generation.

## Energy

Chemical engineers continue to play a pivotal role in the transition towards a net zero carbon future through the development of carbon-free, low-carbon and renewable energy systems, including electric and fuel cells, biofuels, nuclear power, and hydrogen. Chemical engineers work with scientists and diverse stakeholders to develop smart manufacturing processes and systems with improved efficiency and lower environmental impact. They engage in the development of sustainable infrastructure, applying digitalisation, for the effective delivery of energy and storage of surplus energy, thereby addressing the challenges of the energy trilemma: security, affordability, or sustainability? Chemical engineers help develop and deploy decarbonising technologies, such as electrical energy storage systems, carbon capture and storage (CCS) or carbon capture utilisation and storage (CCUS). Existing processes can be improved through sustainable design, including better utilisation of waste heat, process integration, and integrated supply chains. Chemical engineers bring overall systems thinking and life cycle analysis to meet these and future energy challenges and are well placed to consider safety and environment in the design, development, operation and decommissioning of energy systems and infrastructure.

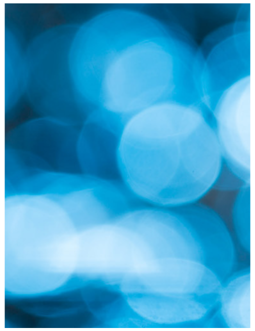


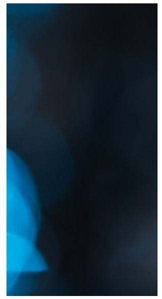











## Food

Global food production, which has until now managed to remain in equilibrium with the land and water use, is under sustained pressure due to increases in global population, climate change and conflict. Improved agricultural production techniques alone cannot address this challenge. Chemical engineers can play a significant role in this area by applying systems thinking and advanced engineering principles through initiatives such as minimising energy and water use, and application of novel technologies and innovation. New approaches and solutions could include sustainable fertilisers, high-intensity farming, land and water supply management, pest control chemicals, smart packaging, energy recovery technologies, and improved food processing and supply chains.

## Sustainable wellbeing

The fast-paced life lived by many people in urban areas can have an impact on physical, mental, and social wellbeing. Chemical engineers play an important role in enabling health and social wellbeing of society through developing new products and efficient manufacturing processes with reduced environmental footprint. Chemical engineers champion the design of sustainable cities through decarbonised building construction, and efficient use of construction materials, energy and resources for building and maintenance. A similar approach is used in sustainable industrial design, where new materials and manufacturing processes are designed to achieve greater efficiency, reduced ecological footprints, and use of renewable feedstocks.

Chemical engineers play a significant role in developing and scaling up of vaccines (eg antibody and antiviral COVID-19 vaccines). Through innovation in drug formulation development, chemical engineers are improving cold-chain transport to enable medicines to be used in parts of the world without highly developed refrigeration systems. Chemical engineering principles can be applied successfully to scale pharmaceutical process (up or down), resulting in reduced manufacturing complexity, improved cost, and equipment effectiveness. Biochemical engineering offers huge potential to improve health and wellbeing through drug discovery, shifting from small molecule drugs to biopharma products, advanced therapeutics production, and developing new formulations to avoid the requirement of cold-chain distribution.

## Resources and manufacturing

Manufacturing processes present multiple chemical engineering challenges, from primary resource extraction, raw materials processing, through to finished product creation across many industries including mining, bulk chemicals, industrial gases, and fine chemicals. Chemical engineers drive the development and delivery of new technologies, processes and products which increase requirements for raw materials and minerals. They can significantly improve minerals extraction processes, particularly though improving water and energy efficiency, resource recovery, and reducing carbon emissions.

Chemical engineers also play an important role in identifying and exploiting renewable resources, optimising supply chains, and implementing lean processes. They can design multi-purpose production lines accommodating different products through employing digital tools such as artificial intelligence and machine learning. Improved product formulations, recycling and recovery of materials reduce the environmental impact of the industry, along with better regulation and long-term planning.

## Conclusion

The contribution of chemical engineers across the four important themes of energy, food, water and wellbeing cannot be overstated. With insights developed from IChemE's centenary, there is huge scope to raise the profile of the chemical engineering profession and align its future objectives and activities more closely to the UN SDGs. Key to this will be identifying which SDGs are most relevant to the profession, and for stakeholders and policymakers to understand that *Chemical Engineering Matters*.

# Ethics, values and diversity

Ethics needs to be embedded in everything engineers do, covering technical as well as societal issues. Chemical engineers must operate to the highest ethical standards and act in the public interest at all times. Leadership and communication are vital, and the profession must also demonstrate honesty and integrity, accuracy and rigour as it upholds respect for life, law, the environment and public good.

Ethical behaviour encompasses sustainability (including climate change), safety, health and the environment, and equality, diversity and inclusion (ED&I).

## Ethical responsibility

Ethical behaviour builds trust in the profession. An ethical culture requires commitment from individuals and organisations, throughout an individual's career, and across all shapes and sizes of companies and educational organisations.

Taking an ethical approach requires self-regulation, as well as complying with regulations. Chemical engineers and those they manage need to act to safeguard the physical and social environment, and to act when they observe any form of wrongdoing. Such action may be to raise a concern or to support a colleague who, in good faith raises a concern. Where there is danger, risk, malpractice or wrongdoing which could result in significant harm to others, chemical engineers have an ethical responsibility to raise concerns with persons or organisations that have the power to halt or penalise unethical behaviours.[5]

## Equality, diversity and inclusion

Recognising diversity and ensuring inclusion are essential elements of good business practice. An inclusive culture supports engagement and commitment from staff and contractors at all levels, and diversity fosters innovation and productivity. As members of an ethical profession, chemical engineers are encouraged to lead by example, treating colleagues and clients fairly and without bias.

## The role of IChemE

IChemE's strategy continues to support activity which embeds ethics throughout the profession. This ranges from accreditation of degree courses and expectations of their content, to training courses, including through the *Sustainability Hub*. Recent work of the learned society has promoted awareness and understanding of ethical and responsible use of digitalisation, and has focused on responsible production. IChemE's position statement on climate change sets out the role of the profession in addressing the global challenge of climate change and the just transition to a low-carbon future.

As a signatory to the UK's Royal Academy of Engineering Diversity Concordat and the UK Science Council's Declaration on Diversity, Equality and Inclusion, IChemE recognises and values diversity. This includes, among others, gender, ability, age, sexual orientation, belief, family and cultural background.

IChemE's vision is to make ED&I part of all its activities and membership groups.

IChemE Code of Professional Conduct requires members "*to uphold the dignity and reputation of their profession and safeguard the public interest*".[6]

# Context: society, policy and economics

## Disruption and uncertainty

The world requires insightful leadership during this current period which is characterised by global uncertainty, with multiple sources of volatility and pressure.

Events such as the global COVID-19 pandemic, the war in Ukraine and the flow-on impacts to world trade have impacted society, business and governments, challenged supply chains, and exposed new risks and opportunities. Geopolitics has changed. Skills shortages exist across multiple industries in global and local economies. There's an increased awareness of and concern about biodiversity and the biosecurity threats affecting health and supply chains.

In 2020 the world saw the biggest economic contraction since the Great Depression. In 2022, inflation soared to the highest level in four decades in many countries, accompanied by market volatility. As central banks tighten monetary policy, raising interest rates to target inflation, this puts pressure on investment by government, investors, and households.

Governments face a more constrained fiscal environment. Rising debt levels, tight labour markets and recessionary risks inhibit effective investment in infrastructure and innovation.

Regulators are focusing on actions to manage risk by increasing system resilience against threats from the impact of COVID-19, geopolitical tensions from the invasion of Ukraine, rising inflation, increasing interest rates, cybersecurity, and so-called 'greenwashing'. In turn, this impacts businesses and jobs.

The COP26 meeting in Glasgow demonstrated a shift by governments, business and investors towards increased action to minimise and mitigate climate change, to decarbonise industries, and to support a just and sustainable energy transition.

This is a period of rapid technological change. As economies undergo structural change, industries and workforces are disrupted. Whilst some industries are in decline, other industries are expanding rapidly, and new ones are emerging in response to the challenges and opportunities.

There are also changes in demographics, working patterns, jobs and workforce. Governments, organisations and individuals must adapt. Labour markets are tight. To fill the skill shortages, there is demand for professionals with engineering and technology skills. The current changes are significant in historical terms, because of the speed of the change.

Uncertainty, disruption and shortages are significant challenges for investment, productivity and growth.

## Changed expectations

Expectations of stakeholders have changed during the past decade.

There is increased community interest and stakeholder activism in matters relating to environmental, social and governance (ESG) issues. This includes significant and rapid change in expectations of the public, investors, insurers, corporations, and government about sustainability and climate change. Good information management, along with cybersecurity and resilience, is extremely important now for businesses' public reputations.

Businesses face higher expectations from shareholders, directors, lenders and insurers about risk management and strategic agility. These expectations include an increased focus on risk exposures to climate change, ESG claims, inflation, interest rates, cybersecurity, and biosecurity. Stakeholder expectations are impacting business goals, strategies, and operations.

> *"...challenges also tell us where the most powerful innovation can be found, when we see a different future and leverage science to create it."*
> (CSIRO Chief Executive Dr Larry Marshall, 2022)

## Megatrends

Megatrends are trajectories of change that typically unfold over years or decades and have the potential for substantial and transformative impact. They help inform long-term strategic and policy objectives.

Megatrends help us to understand the challenges and massive opportunities that will shape our future.

CSIRO's 2022 report identified seven global megatrends: 'Adapting to climate change; Leaner, cleaner and greener; The escalating health imperative; Geopolitical shifts; Diving into digital; Increasingly autonomous; and Unlocking the human dimension'.[7]

## Global and local risks

Facing so many risks, strategic focus is shifting to resilience, adaptation, mitigation, and agility. As the world becomes more complex, this provides opportunities as well as risks.

Security concerns and events such as the energy crisis, Brexit and the war in Ukraine, are challenging free global movement of trade, finances and people, and are intensifying national efforts to build resilience and localise supply chains. However, a retreat from globalisation would reduce standards of living. The political dilemma also impacts the distribution of wealth and environmental damage.

The impacts of disruptions, uncertainty, changing expectations and risks will be uneven around the world. The ability of economies to adjust and adapt will be variable. Disruption and rapid change will require a just transition, where the transition will progress differently in different parts of the world.

The World Economic Forum's 2022 *Global Risks Report*[8] highlights challenges and tensions of different levels of economic recovery following the COVID-19 pandemic in different parts of the world. The importance of international collaboration, building social cohesion and boosting employment is stressed, in the context of risks related to increasing social inequality, climate change, cybersecurity failures and barriers to migration.

## Frameworks for co-operation

Countries participating in COP26 made new commitments to finance losses relating to climate change and mitigate its impact, focusing on initiatives for emissions targets, decarbonisation of industries and road transport, nature-related financial disclosures, reduction in methane emissions, and global investment for climate change mitigation and adaptation.

The *2030 Agenda for Sustainable Development*,[9] is an action plan committed to sustainable development – economic, social and environmental – adopted by all United Nations Member States in 2015. Its focus is on a global partnership that promotes prosperity while also protecting the planet. The Agenda set 17 Sustainable Development Goals (SDGs), which are broad and interrelated, with measurable targets.

## The role of chemical engineers

Global society faces challenges for the security of energy, water, food, and health. Governments will face challenges to meet climate change commitments.

These are core areas of chemical engineering. Sustainability, decarbonisation, energy, pharmaceuticals, food and drink, and clean drinking water are just some of the areas where chemical engineering plays a central role.

Chemical engineers bring relevant skills and experience to shaping the future and addressing systemic challenges as leaders in the global and local team effort. These are shared problems requiring the best engineering practice and a co-operative, multidisciplinary approach. Professions, governments, corporations and society will need to work together to address many big challenges. This requires systems thinking and co-design with other experts and with stakeholders. Chemical engineers are key leaders contributing to policy development and industry solutions. For accurate science-based policy and to action the necessary transformation, chemical engineers provide practical science-based information and promote solutions – to achieve the SDGs, decarbonisation, energy transition, net zero targets, circular economy and other sustainability initiatives.

As organisations need to move faster, this is driving rapid changes in skills required by existing engineers. The workforce will undergo more job transitions. There will be changes in employment patterns as chemical engineers move into other sectors. Professionals will need to be flexible and continually engage in lifelong learning for continuous professional development, including upskilling and reskilling.

Digitalisation is increasingly ubiquitous across process industries, including the further uptake of internet of things (IoT) devices, advanced process control, machine learning and artificial intelligence, and the use of big data. Chemical engineers are required to purposefully leverage these technologies and new ways of working in industry.

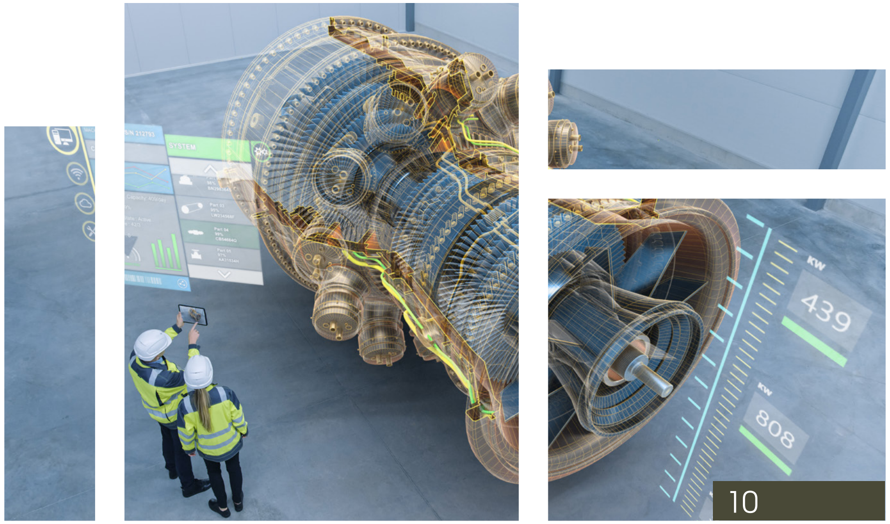
Education must change to meet these trends. Broader entry routes into the engineering profession will need to be developed. Engineering education programmes will need to be responsive to changes.

## IChemE thought leadership

IChemE has published a position on climate change to drive action, influence and reporting.[10]

In addition IChemE has defined three *Learned Society Priority Topics*,[11] to focus learned society activities for societal benefit:

- **Responsible Production (including climate change, energy transition, sustainability and circular economy);**
- **Major Hazards Management and process safety;**
- **Digitalisation (promoting adoption and advancement of digital tools in processes, for economic and societal benefit).**



# The fundamentals: safety and risk

## Disruption and uncertainty

Chemical engineers must manage risk and achieve safety in every aspect of their work, irrespective of the sector. Major Hazards Management, at the heart of which is process safety, is one of the three Priority Topics for IChemE's work as a learned society, alongside Responsible Production and Digitalisation. There are many different types of risk and uncertainty – environmental risks, especially weather events driven by climate change, personal risks, transition risks, etc, though the most core to chemical engineering are process safety and major hazards management.

IChemE is committed to working with government, regulators and other stakeholders to build a common understanding of risk, and to collaborate and share experience with leaders and other professional bodies. These relationships aim to develop a culture that delivers real improvements in safety, health and environmental performance.

IChemE has focused on major hazards management, as this relies on systematic approaches to process safety and management, but also has relevance for non-process industry hazards, for example in the aviation sector. There is much to be shared and learned from tragedies such as Boeing 737 crashes which were due to software bugs, and the Federal Aviation Administration (FAA) allowing Boeing to self-certify the changes in software. Chemical engineering expertise on risk management can also contribute to other disciplines. For example, the report into UK building regulations by former IChemE president Dame Judith Hackitt that followed the Grenfell tragedy concluded that the application of systems thinking could have helped with understanding and managing the risks.[13]

## Risk management

Good regulation is enabling by nature and strikes a balance of what is reasonable and practical to reduce risk to a tolerable level. IChemE supports non-prescriptive, goal-based regulation that puts the legal duty on the organisation that creates the risk. Effective regulation establishes and maintains public confidence. This is especially important with the increase in climate change driven incidents described as Natural Hazard Triggering Technological Disasters (Natech) – where new methods of risk management must be applied, and new technologies rolled out in the drive towards net zero.

While approaches to risk management are well established, new digital tools are offering new ways to identify and manage risks, for example with augmented reality used in training, digital twins for identifying hazards, and digital monitoring and controls. At the same time, changing technologies introduce new risks, eg cyber attacks, or hazards associated with new energy vectors.

## IChemE initiatives

The IChemE Safety Centre (ISC), launched in January 2014, brings together operators, service providers, regulators and academia to share and learn to improve process safety outcomes globally.

ISC develops guidance for industry and academia to help share learning. In 2021, it released Delta HAZOP, a new method of risk assessment that focuses on creeping changes and can be used when traditional HAZOP outputs are diminishing.

IChemE's comprehensive suite of safety training covers the fundamentals of process safety; human factors in process safety, leadership and culture; and other aspects of process safety. The *Loss Prevention Bulletin* – a bimonthly publication sharing learning and good practice among those who are engaged in process safety – was made available to all members of IChemE free of charge in 2021.

Partnering with others to share experiences is key to IChemE's work, and in the safety area takes place through the *Hazards* symposia and the partnership with the Mary Kay O'Connor Process Safety Center at Texas A&M University. Further partnerships will be instrumental in delivering IChemE's ambitions of supporting a sustainable society.

Guidance, including the ISO 37000 standard published in 2021, emphasises the role of corporate governance. Effective corporate governance is required to achieve process safety outcomes, because leadership starts at the top. The ISC supports this via process safety leadership and culture training for executives and non-executive directors, addressing the knowledge gap of an organisation's decision makers. IChemE is now leading a project to map the process safety competencies that chemical engineers require through the course of their careers, investigating how lessons from incidents can be shared more effectively, and will be collaborating with others on projects covering natural hazards, new technologies and consistent applications of good practices.

IChemE offers the Professional Process Safety Engineer registration, which provides public recognition to peer-reviewed practitioners working in process safety related roles.

# The fundamentals: education, training and skills

The areas and technologies in which chemical engineers work is changing, as are the tools and techniques they use. The need for a just transition to adapt to climate change and meet global net zero ambitions is driving huge changes across industry, while the rapid development of new digital tools and the arrival of industry 4.0 has revolutionised the tools and skills required.

Education and training have to be constantly reviewed and updated to keep pace with this.

## IChemE accreditation and Chartered status

IChemE accredits over 300 master's, bachelor's and diploma higher education programmes at 67 universities in 15 countries.

The accreditation process is not prescriptive; rather, it specifies the learning outcomes required of today's chemical engineering graduate. New graduates must acquire the skills to perform in a wide variety of roles across the four vistas. IChemE's accreditation guidelines are reviewed regularly in response to changing international trends.

Accredited degrees provide graduates with a clear pathway to qualification as a Chartered Engineer (CEng) or Incorporated Engineer (IEng). IChemE's range of membership grades suits chemical engineers at all stages of their career, working in different industries and careers. They include student, associate, affiliate and technician member grades and ten different professional registrations.

## Promoting career choices

In addition to its higher education work, IChemE supports employers and trainers along the talent pipeline.

In 2021, IChemE published a series of videos on YouTube titled '*Your career in chemical engineering*' in which members at all levels of experience and in a range of sectors talk about their career journeys.

Meanwhile, a collection of career development materials about the skills transition offers practical advice about switching between industry sectors, and profiles a broad range of chemical engineers working outside the hydrocarbon sector that has traditionally been the mainstay of chemical engineers – covering everything from hydrogen applications to dairy processing, and battery technologies to water treatment.

## Education resources

IChemE supports the development of chemical engineering education through its academic journal, *Education for Chemical Engineers*, and regular coverage of the latest advances in education tools and techniques in its magazine, *The Chemical Engineer*. Several special interest groups (SIGs) have developed or are working on educational resources to equip educators with case studies and materials from a range of sectors and applications, such as safety and loss prevention, nuclear power, and pharmaceuticals.

## Continuing professional development (CPD)

In a rapidly-changing industry, CPD is vital to maintain and develop new skills, and Chartered Chemical Engineers must show they are actively maintaining their CPD, via any appropriate route. CPD is particularly important with regards to safety, sustainability, and digital skills. IChemE's *Sustainability Hub*, launched in 2021, provides an expanding range of entry-level training, and more advanced training courses are being developed. Formal training is just one of the many forms of CPD, which also includes on-the-job learning, and peer-to-peer knowledge exchange through technical webinars. IChemE's *Knowledge Hub* provides central access to tens of thousands of peer-reviewed resources.

## Company training

IChemE supports accredited company training schemes at almost 60 global employers alongside a diverse offer of more than 80 training courses in both technical topics and transferable skills. IChemE will continue to provide high-quality professional development, training, and support for the chemical engineering community in response to the challenges and potential solutions described in the four vistas.

# The fundamentals: chemical engineering research and innovation

Chemical and process engineering is at the forefront of addressing the UN Sustainable Development Goals. Chemical engineering researchers and innovators in both academia and industry play a key part in this change.

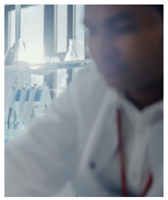
Addressing societal challenges such as climate change, energy and mobility; food, bioeconomy, natural resources and environment; health; and digitalisation in industry, will require chemical engineers' skills and chemical engineering tools. These need to be applied across a wide and varied range of sectors and are supported by the research community with foresight and vision to drive innovation for sustainability.

Like other disciplines, chemical engineering is subject to huge changes. Process technology, transport processes and the classical unit operations will remain at the core, but chemical engineers must pay more attention to molecular transformations along with biological systems and concepts, while fully exploiting concepts from other disciplines, such as molecular modelling, quantum chemistry and synthetic biology.

Use of digitalisation in chemical engineering research and a focus on responsible production will drive industry productivity and sustainability. The concepts of systems thinking will provide a broad integrating framework. The boundaries between research and implementation, and science and engineering will become increasingly blurred. Chemical engineers manipulate molecules, as well as scaling up processes and optimising economic and environmental performance.

## Process and product innovation

Responsible, sustainable production requires innovation, to develop, design, build and operate clean, efficient and economically viable chemical processes, preferentially using renewable resources. For this purpose, chemical engineers apply their knowledge of processes and systems in combination with expertise in catalysis, nanotechnology, bio-engineering, materials, electronics, computation, etc.



Sustainable development is driving the need for new products, such as novel batteries and bio-based materials. Product function and cradle-to-grave environmental impact must both be considered when developing these new products, typically requiring innovative processes for their production. Therefore, chemical engineers need knowledge and skills for product innovation as much as for process innovation.

## Education and academic challenges

Responsible development, design, operation, and improvement of sustainable chemical processes presents significant challenges for practising chemical engineers, and for those who educate them. Undergraduate courses and postgraduate training need to address a wide range of learning outcomes, ensuring that fundamental knowledge and skills of the subject are solidly embedded, and that research and teaching are linked for mutual benefit.

The discipline must adopt new concepts and integrate them into curricula and build more productive, multifaceted and effective relationships between researchers in academia and industry, to facilitate implementation of innovative and sustainable processes in industry. IChemE, working with other science and engineering institutions, is calling for adequate investment in the research base, and for recognition and incentives for first-rate teaching as well as first-rate research. IChemE continues to support the dissemination of research at conferences such as *ChemEngDayUK*, *Chemeca*, *Hazards* and the *Symposium of Malaysian Chemical Engineers*. In addition, journals published by IChemE in association with Elsevier provide highly reputable platforms for the publication of research in the important areas of carbon capture, responsible production, process safety and digitalisation.

## Funding research for the future

Some of the brightest and best chemical engineers pursue a career in academia, typically because they are passionate about their discipline area. There, their research can underpin development, design, analysis, and optimisation of novel processes and products to support a sustainable future. Furthermore, their teaching shapes the learning of generations of future graduates who will contribute to a more sustainable future.

However, especially in times of economic upheaval and multiple conflicting priorities, public and private funding for chemical engineering research can be in short supply. Nevertheless, it is vital to demonstrate impact and publicise and promote the profession and the difference that it can make, more consistently and more compellingly than ever before. Professional institutions such as IChemE should facilitate collaboration between researchers, funding bodies and industry to build a confident and outward-looking international chemical engineering community that will play its part fully in building a more sustainable future.

# The sustainable water vista

Water is fundamental to life, but it is a limited resource. Ensuring that people have access to clean water is a significant global challenge. It is essential that there is a balance between supply and demand. This requires behavioural change and technological innovation.

One in four people globally do not have access to safe drinking water, according to Unicef.[12]

Population growth, industrialisation and climate change continue to increase demand for potable, process, and agricultural water supplies. This is putting increased pressure on water supplies.

Water scarcity is being aggravated by interrelated environmental problems – eg desertification, salination, pollution and climate change – as well as overextraction and large-scale national and international water diversion. Chemical engineers can provide advanced technologies and processes to improve the sustainability of municipal and industrial water supplies and treatment of wastewater.

## Recycling and reusing water

Chemical engineers have an essential role to play in resolving the challenges associated with recycling and reusing wastewater, in municipal and industrial settings. Technology challenges to treat or recycle water, remove contaminants (at macro and micro levels) and dispose of associated by-products, such as concentrated saline, are accompanied by social issues, such as a hesitancy to recycle wastewater to produce drinking water.

As well as being instrumental in providing people and industry with clean water, chemical engineers aim to improve the energy efficiency of water conservation and treatment.

Producing clean, safe water, making it readily available, and improving sanitation and human waste management are significant global public health challenges. In some parts of the world, desalination is used to provide clean, safe water; however, it is energy intensive. Reuse of wastewater is more sustainable, so should be a priority.

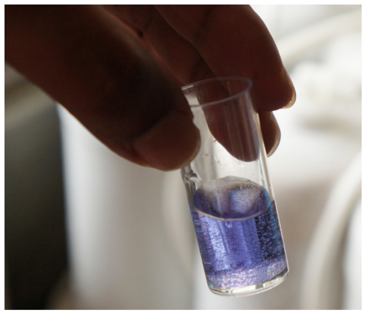
Chemical engineers will play a key role in developing more effective and energy-efficient wastewater treatment and desalination processes.

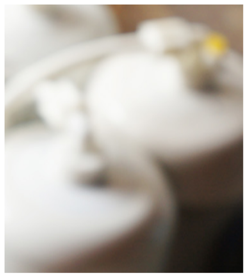
## Maximising the value of waste

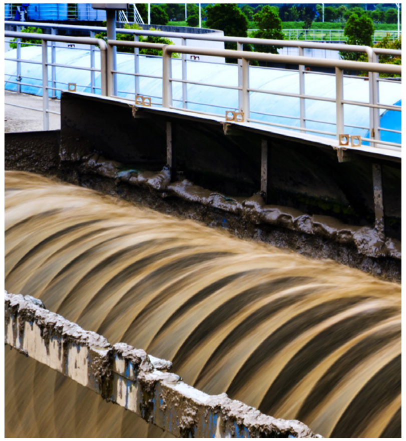
Domestic wastewater is a growing problem in rapidly-expanding urban areas. Industrial wastewater may contain both harmful contaminants and valuable chemicals. Many wastewater treatment solutions are low-cost, particularly on a small scale (eg biofilters and reed beds), but some processes are costly. Wastewater that has not been treated properly can have a significant impact on the human health and the environment.

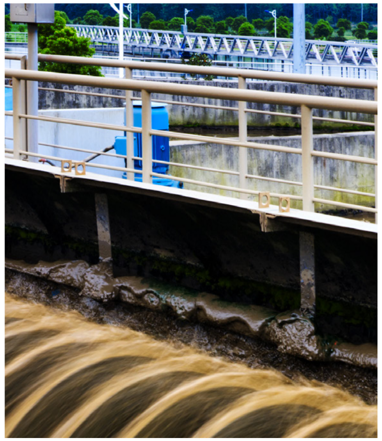
Treating, reusing and recycling water can reduce water and energy consumption and waste, all of which translates into cost savings. Commodities, including nitrates, phosphates, polymers, energy fuels and biogas, can be recovered from wastewater and sludge. Valuable substances, such as trace metals, salts, organic acids and rare earth elements, can be recovered from industrial effluent. Demand for recovered materials will increase as global demand drives up their prices. There will be a greater adoption and development of technologies to recycle process water in industrial plants and municipal water facilities. Advanced digestion, granular treatment processes, fixed-film biomass reactors, anaerobic ammonium oxidation processes and membrane bioreactors play a role in effluent treatment. After being treated, water can be further treated for reuse with ultrafiltration, reverse osmosis, ion exchange, zero liquid discharge and other processes.

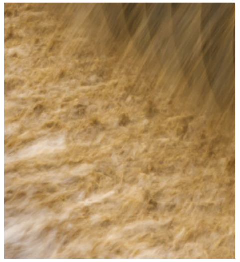
The energy and water industries are likely to become more integrated and there will be greater multidisciplinary working and collaboration. Electricity is already produced from the co-digestion of wastewater, industrial effluent and food waste. Biofuel cells may give access to electricity generation from wastewater, and low-grade heat from power plants and solar power may be used in desalination.











> *“Chemical engineers are being increasingly asked to provide advanced technology solutions and processes to improve the sustainability of municipal and industrial water supplies and treatment of wastewater.”*

## Process safety and efficiency

There is a need to ensure process and product safety throughout the domestic water network and industrial processes. Unexpected or uncontrolled releases pose an environmental risk. Poor-quality drinking water would affect the wider public as well as the environment. The processes and systems used can have other inherent risks, for example, high energy and high pressure.

Chemical engineers will play an essential role in a wider deployment of advanced intelligent control and cybersecurity systems for quality and quantity management throughout the entire water cycle.

## The environment

Chemical engineers play an important role in managing the environmental risks associated with water treatment and discharges, including greenhouse gases, and meeting progressively tighter emissions limits. They will help the industry achieve a more circular economy, reduce capital and operational emissions, and get to net zero carbon emissions.

Utility providers in some regions are already concerned about emerging pollutants, treatment by-products and micropollutants in wastewater and potable water (eg from pharmaceuticals, personal care products and disinfection by-products). There needs to be effective regulation of these pollutants and work to reduce release and impact of these contaminants.

As well as the environmental cost, removal of contaminants has a financial and climate cost; the technologies and processes require investment and emit carbon. Chemical engineers will play a role in all of these areas, working to design out these components or improve processes. However, appropriate regulation is essential.

Improved industry practice, supported by innovative process technology and greater public engagement, will drive stronger performance in water management with a renewed focus on the environmental aspects of water on our planet, protecting catchments, sustaining rivers and working towards rehabilitation and remediation of ecosystems.

## Policy, social awareness and understanding

Society needs to better understand the value of water and the pressures that place reliable water supplies at risk. Improved awareness of concepts such as a water footprint and virtual water will aid understanding and, in turn, lead to more responsible use of water. Different countries have different needs, demands and challenges, so there must be support to facilitate understanding and sharing of best practice and new ideas at global, regional, and local levels. Some regions may choose to introduce universal metering and adopt pricing policies that promote responsible water use.

Sustainable water services require effective planning, construction and maintenance. Infrastructure can last for many decades and therefore the distribution networks, collection systems and treatment plants must be adequate and consider the long-term requirements, the need for flexibility and ability to adapt.

Chemical engineers can engage with decision-makers to ensure there is a strategy to implement improved process technology and practices. The water vista diagram sets out the opportunities for chemical engineers to secure sustainable water supplies; it will be used as a framework for further discussion and priority setting.

**FACTS**

**By 2050, industrial and domestic demand is estimated to increase by 50–80%.** [14]

**Water scarcity affects over 40% of the global population.** [15]

**Around 1,000 children die every day due to preventable water and sanitation-related diarrheal diseases.** [16]

# The sustainable water vista

Current status | Challenges | Future actions/solutions

NOW | NEAR | HORIZON | GAME CHANGERS

## Chemical process technology

- Population growth and increasing industrialisation in developed, emerging and nascent economies
  - Increasing demand for potable and process water
    - Implement more energy-efficient water treatment and purification processes
  - Increasing wastewater and environmental pollution from effluent
    - Promote the use of chemical process technologies to improve water conservation
      - Develop, deploy and promote a hierarchy of sustainable water treatment technologies
    - Need to treat waste and potable water for emerging contaminants
      - Promote energy recovery and value-added wastewater sludge products
        - Work towards improved water cycle modelling
        - Effective regulation and management of micropollutants in water
  - Poor industry and agriculture infrastructure results in water loss
    - Increased biorefining of wastewater sludge
    - Pursue step-change reduction in untreated wastewater sludge applied to agriculture
      - Work with other disciplines to improve water efficiency in agricultural industries
  - Limited reuse of domestic and industrial used water
    - Wider adoption of membrane bioreactors for process water treatment
      - Development and deployment of low-energy desalination technology
  - Wasteful/inefficient treatment of water to potable standard regardless of end-use
    - Increased water recycling and reuse of used water in chemical processes
    - Cost-effective and robust treatment for used/brackish water
      - Collection, treatment and reuse of wastewater for non-potable use

Game changers: Water scarcity restricts life and process industries; Reduced differential pressure, low-energy desalination technology

## Safety and the environment

- Global climate change alters hydrological cycles
  - Improve water conservation using process technology
    - Work to protect water supply network against bioterrorism
  - Limit water process emissions, ie methane and nitrous oxide
    - Work towards zero effluent discharge in all industries
  - Digital technologies deliver construction and process efficiencies
    - Improved catchment management to secure water resources
- Damming for irrigation and power generation resulting in negative environmental impact
  - Strengthen focus on ecosystem rehabilitation and remediation
    - Treatment and disposal of concentrated saline waste
  - Implementation of water-sensitive urban and industry designs
    - Nature-based solutions for flood management, wastewater treatment etc
- Risk of water pollution from mining and industrial processes
  - Greater use of in-line measurement and monitoring of water quality
  - Increased use of system-wide condition monitoring
    - Work to reduce system operating pressures
- Risks associated with water quality, high-energy, high-pressure systems, and cyber terrorism
  - Wider deployment of advanced, intelligent controls, digital twins and cybersecurity
- Contamination with pathogens

Horizon: Increased water scarcity

Game changers: Groundwater exhaustion and pollution; Low cost, efficient processes to remove contaminants from water

## Policy

- Lack of long-term infrastructure
  - Mutual support between industry and governments for implementing technology to support water strategy
    - Regulation drives zero liquid discharge from industry
- Lack of coherent water strategy globally and in different regions
  - Improved sharing of best practice
    - Drought resilient water supply technologies for industry and domestic supply
    - Promote nutrient recovery programmes
      - Develop and implement effective strategies for global and regional water management
- Poor understanding of the economic importance of water
  - Promote innovation in water conservation, reuse and supply
    - Improve process audit and control in the water sector
    - Work with policy and decision-makers to highlight economic, sociological and political challenges relating to water and industry

Game changers: Universal access to safe water

## Society and public support

- Strain on existing water resources
  - Increasing global population leading to greater demand for domestic and agricultural water
    - Improve awareness and understanding of 'virtual water'
    - Promote responsible use of water
  - Unequal use of water in developed vs developing nations
    - Promote understanding of the water footprint concept
    - Highlight true cost of water and areas of use
  - Shortage of technical expertise entering the water industry
    - Promote role of chemical engineers in the water industry
- Water shortages may result in energy and food shortages leading to political and social unrest
  - Work towards use of safe, fit-for-purpose water

# The sustainable energy vista

Modern society relies on energy for many aspects of daily life including heating, cooking, transport, and lighting. Energy also powers industry and commerce, operates equipment, and lights our lives. Global population increases, economic development and industrialisation continue to drive rapid increases in energy demand.

The energy landscape is complex. Meeting energy requirements and providing security of supply while limiting greenhouse gas emissions is a difficult balancing act, even without price volatility driven by external events.

## Climate change and sustainability – people, perceptions, and processes

Widely available carbon-free or ultra-low carbon energy is considered a 'must have' to maintain and improve quality of life sustainably. Governments and industry are committing to decarbonise and meet net zero carbon emissions by 2050. Such commitments require investment, innovation, and action.

Chemical engineers are helping to develop and implement step-change improvements to make existing processes more efficient. Working with scientists and other engineers, they are assessing the benefits and environmental impact of advanced manufacturing processes.

Smart energy management solutions are important, especially given the growth in intermittent renewable energy sources such as wind and solar. These require the development of sustainable infrastructure, including digitalisation, to deliver energy where and when it's needed, and new and effective ways to store energy when there is surplus.

Demand and competition for finite raw mineral and biological resources will continue to increase. Careful resource stewardship requires a greater understanding, development and uptake in industry and society of circular economies and processes to reduce waste, reuse and recycle material and produce resilient products. Chemical engineers are at the heart of this, developing the energy and mass balances needed to provide the foundations for discussion and decision-making.

## Energy security

Energy security is defined as uninterrupted availability of energy sources at an affordable price. Global conditions can impact the security of energy supply, and an over-reliance on a single source runs the risk of disruption and price shocks. An accelerated move towards alternative energy sources will drive increased demand for critical metals and minerals.

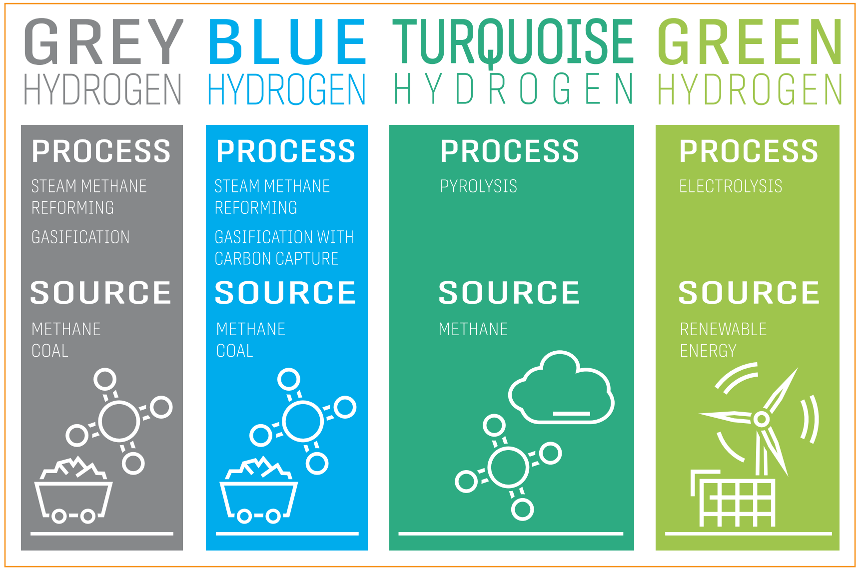
Energy supply needs to be made more secure, to a limited extent, by energy storage. This also helps to increase the contribution of renewable energy.

Some governments may address short-term energy shortages by increased use of fossil fuels, including unconventional gas assets or even coal. Chemical engineers can help mitigate the resulting environmental impacts through carbon capture and storage (CCS) and groundwater remediation. Expanded energy storage can improve resilience to increased climate risk (eg extreme weather) and cyber attacks.

## The future energy mix

Renewable energy will increasingly power homes and industry. However, only in a few countries and energy scenarios is 100% renewable energy possible. Thus, the future will see a mix of energy sources including, for some regions, nuclear power.

Hydrogen is being suggested as an alternative energy carrier in many industries. However, it is only as clean as the process used to generate it. Long-term sustainability will rely on massive scale-up of 'green hydrogen', where renewable power is used to electrolyse water. The safety implications of widespread use of hydrogen also need to be carefully considered, as hydrogen is highly flammable and volatile. Chemical engineers are working on processes across the hydrogen spectrum.



Nuclear power is an alternative source of low-carbon electricity. Many scenarios show that, to meet net zero, the world needs to install more nuclear capacity, as well as invest in co-generation for hydrogen production, water desalination, and process heating. Chemical engineers will play a huge part in managing nuclear chemical systems and coupling reactors with the processes they support.

To continue global trade in goods and personal mobility and travel, the world needs to decarbonise transportation. Options include renewable fuels, eg fuels derived from biomass (food and non-food crops and agricultural wastes) or other waste (eg plastics) and management at source, eg electric battery and fuel cell propulsion. Any greenhouse gas generation in the latter must be managed by the energy source.

It is predicted that fossil fuel use will continue in the short- to medium-term, but the impact can be greatly reduced by capturing and storing carbon emissions.

Renewable energy technologies such as wind, wave, and tidal power, and even solar photovoltaics, present new challenges. The devices are variable in size, and energy production can be intermittent, which requires new approaches to managing supply and demand. Local generation and perhaps re-distribution at an international scale mean that energy storage and system resilience will be essential.

## Smoothing the peaks

The increased use of digital tools to manage supply and demand, within both fossil fuels and renewables industries, will be a significant factor in the growth of electricity demand and consumption in the coming years. Alongside this, electricity storage, both small- and large-scale, can smooth the peaks and troughs in supply and demand and improve reliability. In many parts of the world, this will also require major upgrades to transmission infrastructure and distribution networks.

Chemical engineers play a large part in developing, deploying and using electricity energy storage systems, for example by designing the processes to produce advanced batteries and super-capacitors and to replace cobalt and nickel in grid-scale battery systems.

Using compressed air energy storage systems (where geography permits) to store power and other long-term storage achieved through biomass, bio-gas, ammonia, synthetic fuels and hydrogen, are direct chemical engineering applications.





## Carbon capture, utilisation and storage

To combat climate change and keep the average global warming less than 2°C above pre-industrial levels, the Intergovernmental Panel on Climate Change (IPCC) considers that CO2 levels must be kept below 450 ppm. This will require emissions abatement and CO2 removal through technological and nature-based solutions.

Carbon capture and storage (CCS) is proven technology with commercial facilities in operation and others in construction and development. In 2021, the combined capacity of these operating or foreseen global CCS facilities could capture almost 150m t/y CO2. These installations cover power generation, energy intensive industries (eg iron and steel), refining and manufacture of chemicals such as ethanol and fertiliser. The extension to CCUS via technologies such as bioenergy with CCS, or the application of CCS to energy-from-waste plants (depending on waste stream), have the potential to help realise CO2 removal to further support net zero targets.

CCUS requires a transport network and geological storage, with significant investment. CCS can reduce carbon emissions at the cost of operational efficiency, often to the detriment of the overall process economics. However, using CO2 as a feedstock for chemical processes, microalgae or plant growth and mineral carbonation within CCUS can offset the process economics, but careful attention must be directed towards energy balances and rigorous life cycle analysis for new processes.

Adoption of CCUS depends heavily on carbon pricing and government intervention. Equal effort must be directed towards the development and widespread deployment of truly sustainable and commercially viable processes based on renewable energy.

## integration

Existing processes can become more sustainable through efficiency improvements and the use of more efficient and sustainable energy. Better use of waste heat, process integration and more integrated supply chains all play their part. Infrastructure needs to be designed with resilience, safety and sustainability in mind. Energy solutions need to embrace systems thinking and life cycle analysis, with reuse and recovery at the end-of-life considered from the outset. This challenge applies to all energy systems, from wind turbines and solar cells to nuclear reactors and spent fuel management.

Safety and environmental impact are key considerations which need to be continuously improved. Chemical engineers are instrumental in achieving this at all stages of the energy infrastructure lifecycle, from design to decommissioning and – where required – remediation.

## The role of policy, society and ethics

A sustainable energy strategy requires long-term thinking and must benefit society, the economy and the environment. The pace of change will vary from nation to nation. Developed countries, which have already capitalised on the use of previously abundant natural resources, must take the lead using their knowledge and infrastructure to drive change.

Making this happen requires the international consensus that often proves elusive. Nevertheless, we can act today to reduce the impact on the planet and address the uncertainties and instabilities that have the potential to spark global conflict.

**FACTS**

**2019: 81% of global energy supply comes from fossil fuels.** [17]

**IPCC modelling (2018) envisaged that 80% of electricity generation in 2050 will be supplied by low-carbon sources.** [18]

**The Paris Agreement empowers all countries to act to prevent average global temperatures rising above 2°C.** [19]

# The sustainable energy vista

# The sustainable food vista

Major improvements in agricultural production during the latter half of the 20th Century have ensured that, to date, global food production has kept pace with population growth. However, land and water are finite resources, with competing demands upon them. Growing populations and improving living standards in the developing world create demand for more food, especially protein-rich foods, where these are water-, land- and energy-intensive. Food production is an energy- and resource-intensive process: more than 20% of greenhouse gas emissions now come from agriculture, forestry and other land use. Climate change is already affecting crops and harvests due to changing weather and reduced availability of suitable land and water.

Improving agricultural production techniques will not alone provide sufficient food and reduce climate impacts. A more holistic approach that uses science and engineering solutions is needed for food production to meet demand without increasing energy, water or land use, while minimising waste. Chemical engineers can apply systems thinking and deploy life cycle analysis to map the overall environmental impact of food production and consumption.

## Minimising environmental impact

There are many areas where agriculture can benefit from good science and engineering, novel technologies and process innovation. These might include more sustainable and alternative fertilisers, or the use of new measurement technologies and analytics to minimise resource use and pollution. High-intensity farming, such as urban and vertical farming, using renewable energy, and remediation processes for both land and water supplies, can also reduce environmental impact.

Pests and diseases must be controlled in a safe and sustainable way, for example by using chemicals such as pheromones, which can manipulate the behaviour of pests and beneficial insects, and by developing more benign alternatives to traditional pesticides and fertilisers.

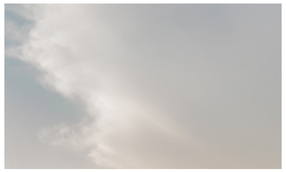
The development of alternative proteins from fungi, plants, insects, algae and cultivated animal cells can reduce the greenhouse gas impact of agriculture, alongside improving the sustainability of traditional protein sources.

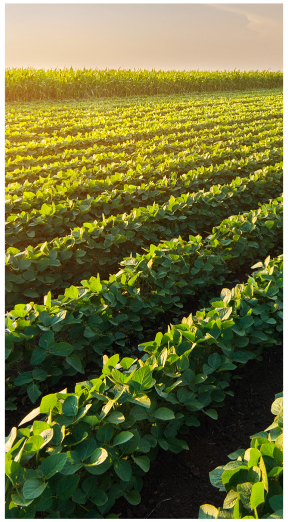
## Efficiency and waste

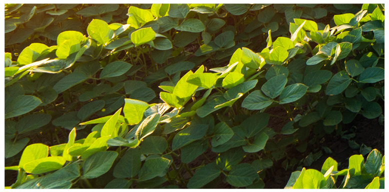
The World Food Programme estimates that around a third of the food produced each year is lost or wasted. Smart packaging can reduce food waste by prolonging shelf life, but its use must be restricted to where it is most needed, and packaging must be fit for reuse and recycling.

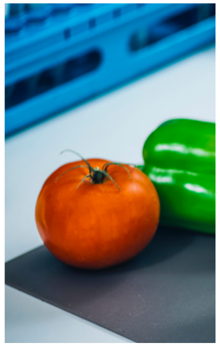
Food waste can be recycled through composting or landspreading. Where this is not feasible, energy recovery from food waste through incineration, anaerobic digestion, pyrolysis, gasification or production of fuels and chemicals through fermentation is preferable to sending food waste to landfill. Chemical engineers can achieve step-change improvements to reduce and valorise food waste.

Strategies are needed to use food waste more effectively, especially managing the large quantities of wastewater generated, and to safeguard supply of water which is a large and vital part of the food production process.









## Food security

Global inequalities in food availability mean that there are regions of significant population density that cannot be supported by the land around them, often due to climate change and political unrest. Recent geopolitical events have sharpened the focus on food security. More effective transportation and storage of food and drink are a partial solution, but more could be done to enhance local production. Where feasible, chemical engineers can establish local water supplies for drinking, and for appropriate and environmentally sustainable irrigation.

There is a growing realisation that food security means not only mean distribution of carbohydrates but also ensuring equitable access to protein and micronutrients. Better storage and longer shelf life will enable this. Non-food crops can offer new raw materials for energy, construction, fibres, packaging, pharmaceuticals and speciality chemicals, but this diversification must be balanced against the need for land use to grow food. Chemical engineers should work with the farming industry, microbiologists, nutritionists and other disciplines to optimise agricultural output while working to reduce energy consumption and environmental degradation.

Regional and global strategies will be needed to increase innovation and optimise agriculture. Some governments already have policies to ensure food security and support local food production. For example, Australia is largely self-sufficient in food and is a significant exporter to growing Asian markets. It is important to recognise that resource-rich regions will need to provide nutrition to less well-resourced regions. The transfer of these resources needs to be both sustainable and on an equitable basis.

## Process and product safety

Food product safety is achieved by applying good practice, audit and traceability, process safety management and appropriate environmental considerations throughout the supply chain. Digital technologies can enhance traceability and supply chain integrity. Some of these areas are not process safety management issues in the traditional sense, but there should be awareness and understanding of all of these issues within the chemical engineering community.

The food sector needs to improve understanding of the role that genetically-modified (GM) crops can play in meeting global food demand. Understanding the impact of pests and disease outbreaks within crops and livestock is essential.

Greater food production will not be achieved by simply intensifying current agricultural processes, as this can lead to larger or more frequent outbreaks of disease. Although vaccination, fungicides and other treatments may increase in use, so does nature's resistance to them.

## The policy dimension

The sector faces twin challenges of poor or insufficient nutrition for significant numbers of the global population, while elsewhere obesity and associated health issues such as type II diabetes are on the increase.

Improving current strategies and developing new technologies will be key, where chemical engineers must engage with decision makers to ensure these are applied appropriately. Sustainable supply-and-demand requires greater awareness of resource limitations and more holistic end-to-end solutions to produce the most efficient outcomes.

Although there has been significant resistance from the public towards GM crops, they may have a role in addressing climate challenges and the need to increase food production, provided that environmental and product safety needs are met.

The food vista sets out the range of possibilities for chemical engineering in all of these areas and will be used as a framework for discussion and priority setting.

**FACTS**

**Around 930m t of food is wasted every year – 61% from households, 26% from food service and 13% from retail.** [20]

**With 26% of global greenhouse gas emissions linked to food production, food waste accounts for 6% of global emissions.** [21]

**Almost 192m people suffered acute food insecurity in 2021, almost 40m more than in 2020.** [22]

# The sustainable food vista

Current status | Challenges | Future actions/solutions

# The sustainable wellbeing vista

The World Health Organization defines health as a state of physical, mental and social wellbeing and not merely an absence of disease or infirmity.

Social wellbeing comprises many elements, including living in an environment that is healthy, and promotes physical and mental harmony. Chemical engineering plays a fundamental role in facilitating health and social wellbeing to enable people to live healthy and fulfilled lives.

## Sustainable lifestyles

The world is becoming urbanised. Despite recent changes in working patterns to enable more remote working, more people now live in towns and cities than in rural areas. Where urban growth is rapid, development is often haphazard and can have a detrimental impact on the environment. Urban areas need to function as living spaces while meeting the needs of commerce and industry.

To address this challenge, we must realise the concept of the sustainable city. Urban spaces must make the most efficient use of the construction materials, energy and resources needed to build and maintain them by, for example, using data to create digital twins for life cycle analysis of any built environments. It is important to decarbonise construction as well as building operation, as carbon embodied in construction accounts for anywhere between 10–50% of its carbon footprint. In addition, urban spaces of the future need to be flexible enough to respond to changes in use or environmental extremes.

## Sustainable industrial design

Developed nations must lead the way by making fundamental shifts in consumption, recovery, and reuse or recycling. By applying the principles of green engineering from the outset, chemical engineers can help design processes and products that safeguard the environment and facilitate healthy lifestyles, while delivering the resilience and flexibility to adapt to changing requirements and environments. These products can be integrated into the wider supply chain with relatively low capital investment and reduced operating costs, which could then be reduced further through the use of data for process optimisation.

In some cases, new materials or manufacturing processes will be needed to achieve greater atom efficiency, reduced ecological footprints, or to use novel feedstocks, including biomass. Life cycle analysis can be deployed to map energy, water and resource use. Design and optimisation through applying chemical engineering fundamentals, and emerging digital skills such as the use of big data, will improve financial and environmental protection. The leadership and systems thinking that chemical engineers bring will be invaluable in realising lasting, sustainable improvements.

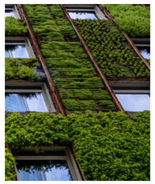
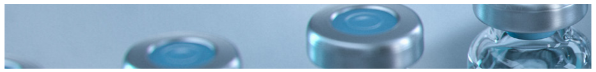
## New pathways in health and pharma

People are living longer, thanks in no small part to developments in healthcare. In developed countries, longevity and the associated demographic shift bring new challenges, including how to ensure physical and mental wellbeing into old age, and how to enable a shrinking workforce to support and pay for the needs of older people.

Pharmaceuticals have largely eradicated many infectious diseases that were common in previous generations, leaving developed countries battling neurodegenerative conditions, cancers, and ailments often attributed to more affluent lifestyles – eg heart disease and type II diabetes. While the health of people in developing countries is improving, chemical engineers are still needed to support access to clean water and sanitation.

The COVID-19 crisis has shown significant scope for improving the global preparedness for a pandemic. Chemical engineers played a significant role in developing and scaling up COVID-19 vaccines and treatments such as antibody and antiviral medicines that have saved countless lives. To manage future pandemics better, global capacity for rapid vaccine development and scaleup must be improved, as must distribution systems, to ensure equity.

> *“Chemical engineers played a significant role in developing and scaling up COVID-19 vaccines and developing treatments that have saved countless lives.”*


By developing more efficient processes, chemical engineers can reduce the cost of pharmaceuticals, while improvements in drug formulation can remove barriers such as cold-chain transport that can limit access to some medicines in some parts of the world. There is also a need to develop new treatment strategies for infections, to counter rising antimicrobial resistance of some infectious agents.

The pharmaceutical industry is continuing to shift from reactive treatment towards prevention-based healthcare. Tools employed are also changing, with much greater use of digital tools requiring chemical engineers to use novel analytics and visualisation technologies.

There are significant cost pressures associated with new product development: responding to changing legislation is a constant challenge for the industry. The pharmaceutical pipeline is long and expensive, and has high attrition rates. Chemical engineering expertise will help reduce the complexity of producing active pharmaceutical ingredients (APIs) and make processes easier to scale up and control. Chemical engineers can also improve cost effectiveness in a whole range of areas from vaccine manufacture and oral dosage formulation to validation and the determination of overall equipment effectiveness.

## Biological and biochemical engineering

Biological and biochemical engineering offer great potential for health and wellbeing, including drug discovery and production of so-called advanced therapeutics. New vaccine platforms, including viral vector and mRNA, which had not been widely used prior to COVID-19, offer a quicker response in pandemic or evolving infectious diseases. Chemical engineers are required to design and operate the manufacturing facilities for fermentation, fill/finish, and also to scale up processes rapidly from lab to commercial. Development of new formulations will avoid the need for cold-chain distribution and potentially move away from injected formulations.

Systems thinking helps bridge the gap between biology and process engineering, and will facilitate the development of personalised medicine and more targeted, cost-effective medicines and therapies. Again, a key enabling technology is data science and machine learning to recognise patterns in disease and demographics, and therefore identify the most suitable treatments.

There is a shift from small molecule drugs to biopharma products. In future, there will be greater use of biosensors. Engineering will play an important role in the growth of biological materials for transplant organs, tissues and bone. Biochemical engineering has considerable potential for application in manufacturing processes such as clean meat production, microbial recycling of plastics, and green chemicals that will use more sustainable feedstocks. However, there is still considerable work to be done to develop and grow the area of biological and biochemical engineering.

Chemical engineers will play a critical role in translating scientific discovery and innovation into high quality processes and products such as new medicines and medical devices.

## Process safety – people and the environment

Maintaining good health is not only about providing healthcare and material goods. It is also about having healthy and safe living environments. It is essential that chemical engineers communicate the concepts of process safety and its management, environmental responsibility and risk to wider groups, including the public, policy- and decision-makers, and non-governmental organisations (NGOs).

**FACTS**

**As of 20 April 2022, there had been 50.4m confirmed cases of COVID-19, including 6.2m directly attributable deaths.** [23]

**COVID-19 has disproportionately affected vulnerable populations, including those who are economically disadvantaged.** [23]

**Air pollution was responsible for around 7m deaths globally in 2016.** [23]

**Stunting as a result of malnutrition has fallen 27% from 2020 to 2022, where some 45.4m under-fives were underweight in 2020. In the same year 38.9m children under five were overweight.** [23]

# The sustainable wellbeing vista

Current status | Challenges | Future actions/solutions

NOW | NEAR | HORIZON | GAME CHANGERS

## Chemical and Biochemical process technology

- Greater demand for products due to increasing population and economic development
  - Demand for new pharma and healthcare products for new diseases and ageing population
    - Increased incidents of antibiotic resistance → Develop new strategies and solutions to healthcare challenges → Increased profile of biological engineering as a strand of chemical engineering → Wider application of biotechnology to primary production and manufacture → Implementation of integrated product and process design strategies
    - Learn from sharing of best practice → Share knowledge across engineering and science disciplines → Wider deployment of engineered drug delivery
    - Promote systems thinking and chemical engineering leadership → Secure a paradigm-shift in energy and resource efficiency
  - Manufacturing can be energy and resource intensive → Integrated feedstock and energy supply chains → Disposable technology for improved safety and reduced product changeover issues → Quality-by-design process development and continuous verification
  - Limited material resources; Need for new technology development → Promote the use of diminishing fossil resources as feedstocks not fuels → Improve processes to access high value and novel products from non-fossil resources → Improve process atom efficiency; Improve material recovery by effective front-end design
  - Continual process equipment change is costly → Promote effective design and validation of manufacturing processes → Wider use of flexible manufacturing processes, miniaturisation and modular components; Flexible, modular process facilities for pilot and full-scale production → Mitigate risk with more efficient and less costly development pipelines
  - Growth of new and existing process industries → Promote role of chemical engineering in non-traditional and emerging fields/industry
- New vaccine platforms
  - Improved formulations for better distribution
  - Rapid responses to new and existing threats
- Cell and gene therapies
  - Step change in treatment outcomes
  - Maximising manufacturing efficiencies to improve global reach

Integrated production and distribution

Cost-effective, customisable personal medicine

Game changers: Widespread low-cost access to medicines and consumer products; Smart medicine

## Safety and the environment

- Process industries are intrinsically hazardous
  - Increasing impact on environment → Risk of pollution from industrial processes; Limited regulation and standards in nascent and emerging economies
  - Increased biopharma poses new biosafety risks
  - → Chemical engineers have a duty of care to manage risk for the public and employers
    - Ensure process safety is acknowledged, understood and implemented at all management levels
    - Work across disciplines to inform and address process safety by open dialogue
    - Support effective communication of risk → Inform public and other stakeholders of risk
    - Increase awareness, understanding and practice of process safety in university courses → Position environmental protection as central to the work of chemical engineers
- Different business models face different challenges and risks → Monitor and work to ensure high safety standards across all business models: large, multinational, SME and contract

Increased risk with Increasing scarcity of rare earth elements and other critical materials used in advanced technologies

Game changers: Low-energy, low-cost material recovery processes

## Policy

- Need for clear policy and strategy
  - Work towards long-term, secure supply chain and resource management strategy → Engage with policy- and decision-makers to develop strategies for local manufacturing and sustainability → Improve value stream management; link supply chain to market place; Support for sustainable local manufacturing
  - Further address end-of-life and reduce waste materials → Wider use of life-cycle analysis → Support, develop and implement move to use of less hazardous materials and processes; Minimise environmental impact → Encourage and support chemical engineers' engagement with policy-makers, opinion-formers and the public
  - Develop strategies for efficient product cycle time: concept to commercialisation → Support integration of distribution into manufacturing strategy → Paradigm-shift in healthcare strategy and approach → Personalised medicine and smart devices; Promote chemical engineering work at the interface with other disciplines → Shift towards more sustainable cities, homes and lifestyles using process and design
- Increasing cost of healthcare → Link industry with regulators to improve product robustness, patient safety and patent integrity

## Society and public support

- Increasing global population and economic development
  - One third of the global population lives in poverty → Promote the role of chemical engineering in novel approaches to providing future healthcare, goods and materials for wellbeing → Pandemic or catastrophic health episode
  - Ageing population changes demand; More complex molecules and formulations, with more combination doses → Shift towards proactive preventative healthcare rather than reactive → Encourage and support interaction of chemical engineers with the public
  - Greater demand for materials, medicines, lifestyle goods and consumer products → Develop new healthcare strategies for an ageing population; Ensure teaching of modern processes/technologies while maintaining a firm foundation of chemical engineering fundamental principles
  - Societal tendency to want more than is needed → Promote responsible consumption and use of materials and goods → Reduce raw material use, embrace material recovery, reuse and recycling
  - Developed markets often rely on imports rather than more efficient local supply → Promote understanding and principles of sustainability

Game changers: Eradicated diseases re-emerge

# Resources and manufacturing

Water, energy, food, and health all contribute to wellbeing. Their creation in turn relies on the availability of raw materials, including mined and biological resources, and of the manufacturing processes required to transform resources to end products. For the element indium, for example, the journey from ore to a fully-charged smartphone is long, and full of chemical engineering challenges.

Chemical engineering is applied throughout the production chain, from extractive industries to manufacturers of bulk and specialty chemicals, industrial and medical gases, materials for manufacturing consumer products, and of consumer products themselves.

## Economics and the global marketplace

Demand for resources has grown sharply, driven by growth in emerging economies, and an increased focus on energy transition has increased demand for many resources, materials and products.

## Raw materials and the extractive industries

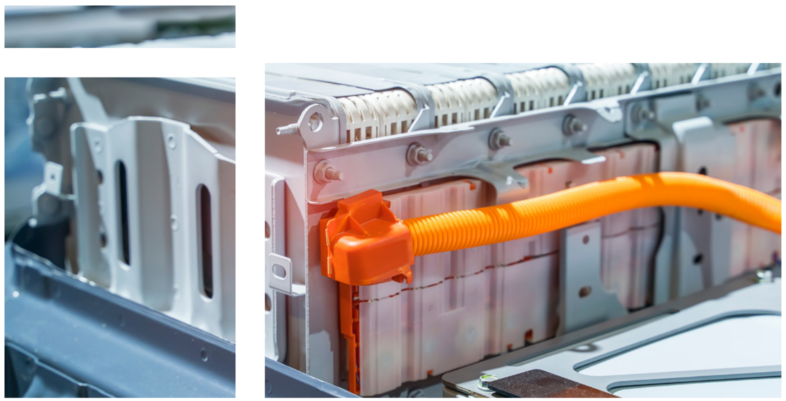
Many common raw materials are mined and extracted from the Earth's crust. These finite resources include coal, oil and gas, metal ores and other minerals, eg carbonates, silicates, phosphates and clays.

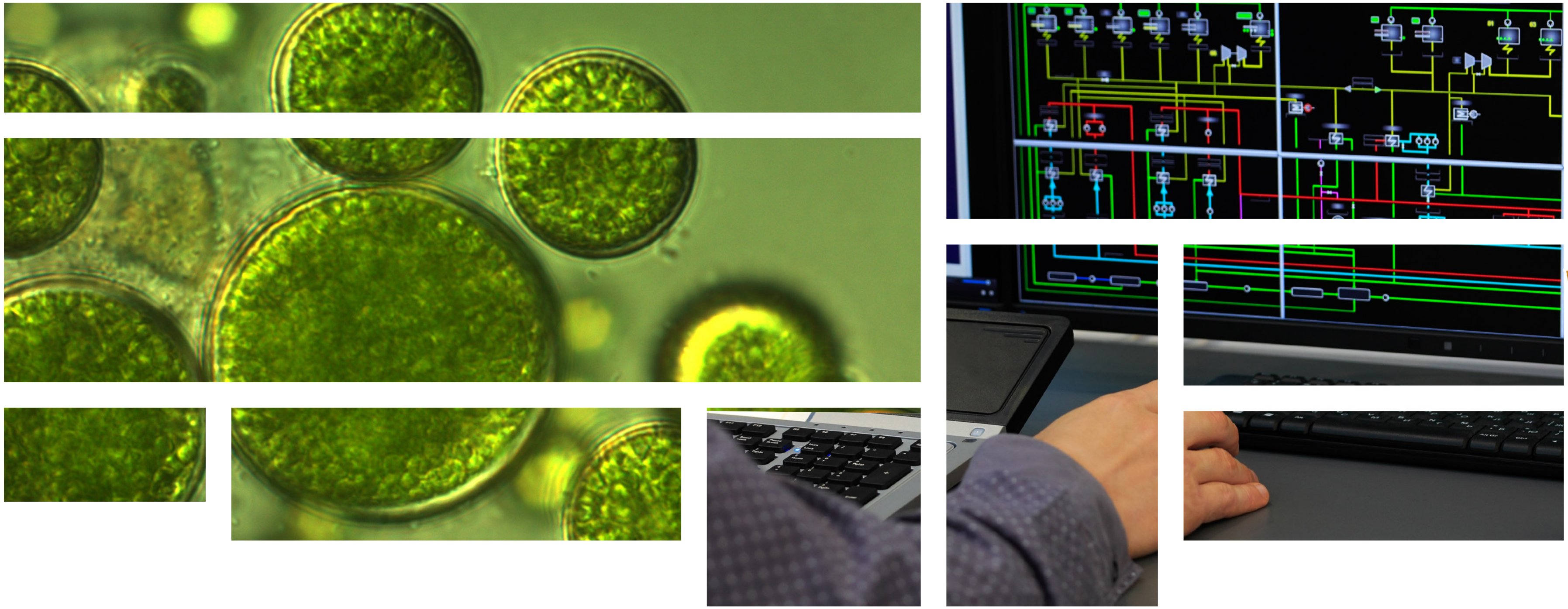
There has been substantial and ongoing growth in the metals and minerals (eg copper, lithium, cobalt, nickel, and graphite) needed to support the transition to renewable energy for power generation and transportation. The processing of most of these critical metals and minerals requires chemical engineering expertise.

There are many challenges in minerals extraction where chemical engineers can make a difference. These include water and energy efficiency, efficient resource recovery, and reducing the contribution to climate change.

Around half the energy used in mining goes into crushing and grinding, accounting for 3% of global power use. Even small efficiency gains here can have a huge effect on global consumption of water and energy, with concomitant benefits of reducing waste, mitigating climate change and cutting costs. Many large mining operations are in water-stressed regions, such as Australia, South Africa and Mongolia. Mining companies are increasing their adoption of dry-stack tailings technology where the mine residues are filtered to a dry friable material. This technology provides twin benefits, a safer residue storage facility with no risk of dam failure, and recovery of process water for reuse.

Resources are finite, and there is constant pressure to find and exploit new reserves. This pressure drives development of new exploration and extraction techniques. Some metals occur in low concentrations in the ores of more major metals, from which they can be recovered if market economics and available processes allow. The iron and steel-making industry emits significant amounts of greenhouse gases, including carbon dioxide, methane, and nitrous oxide, driving global warming. More recycling of waste metal can help to reduce those emissions, as can the move to cleaner, more efficient processes, including using hydrogen to decarbonise the steel production process.





## Renewable resources

The resource industry also includes renewables, such as biomass sourced from land or sea. Chemical engineers can help multidisciplinary teams to identify and develop new, sustainable sources of raw materials. Bio-based raw materials can be derived from agriculture, aquaculture, forestry, and the food industry, yielding a broad range of products such as cotton, paper, plastics, and biofuels.

Fertiliser production needs to move from natural gas feedstocks to more sustainable ones. Hydrogen can help decarbonise steel production. Molecular recycling can reduce reliance on oil and gas feedstocks and enable plastic to be recycled into new high-grade materials. Chemical engineers face the challenge of designing robust processes that can use a diverse range of feedstocks, while meeting rigorous environmental and social standards. Plant lifecycles must be sustainable, from commissioning, through operation to decommissioning.

## Manufacturing

The manufacturing sector has seen upheaval recently. Global production dropped 6.8% in 2020 during the COVID-19 pandemic[24], and while it rebounded in 2021, huge rises in energy costs and threats to energy security will impact future production. Global production and manufacturing sectors contribute 20% of global carbon emissions and consume 54% of the world's energy resources.

Producers of raw materials and manufacturers must respond to the challenge of producing goods and operating global supply chains in a sustainable way, enabling ambitions to transition global emissions to net zero by 2050. As well as cutting emissions, the manufacturing industry will need to conserve resources and minimise waste by implementing a circular economy approach as far as is practicable. Research and development (including product development) can help improve sustainability, reduce carbon footprints and increase efficiency, and chemical engineers can contribute by optimising supply chains and implementing lean processes, leveraging digitalisation wherever possible.

COVID-19 and the war in Ukraine have laid bare the fragility of global supply lines, especially when industry becomes too reliant on a single key supplier of certain goods or resources, or when national self-interest causes governments to block exports of key goods. While the long-term outcomes are not yet known, governments and industry are rethinking their supply strategies and placing greater importance on resilience and security of supply.

Just as processes must be flexible to adapt to changing consumer demands, multi-purpose production lines can accommodate different products. The advantage of steady-state operation is greater efficiency through automation, energy use and consistency. Digital tools are accelerating the transformation, with the use of artificial intelligence, machine learning to improve process efficiencies, or the use of complex modelling to augment existing energy systems to accommodate new energy sources.

Understanding unit operations and process control and applying them to complex systems will require new measurement techniques and a shift in manufacturing design mindsets, which chemical engineers are well suited to bring about. Chemical engineers are integral to developing and operating processes and infrastructure to achieve any such change.

By collaborating with other disciplines, chemical engineers can make processes more efficient and support the transition to a circular economy. This means reducing raw material use and/or designing products from which components can be recovered, reused or recycled at the end of their useful lives. These approaches will be particularly important where resources are already limited.

## Responsible use, reuse, recycling and recovery

Although science and engineering work to develop new methods to access raw materials, we cannot continue indefinitely to extract materials from the Earth. Economic and geopolitical turmoil can disrupt supply, so improving self-reliance through recycling, and reducing extraction of virgin materials makes good business sense.

In many countries and industry sectors, legislation addresses end-of-life of many products. Achieving related circular economies requires innovative design of products and processes, advances in product formulation, and improved recovery and recycling of materials.

While industry works to meet these requirements, society needs to change its 'disposable' mentality. This must be supported by appropriate infrastructure to recover end-of-life products for recycling. There is a pressing need to improve methods for recovering valuable materials in batteries, for example in end-of-life electric or hybrid vehicles.

Extraction of resources and manufacturing can be hazardous activities. The importance of safe processes and operations, to both workers and the environment, cannot be overstated.

Mining, oil, and gas present risk from fires, explosions and uncontrolled gas releases. The areas of concern for manufacturing mainly stem from bulk chemicals handling, toxic intermediates and mechanical hazards. Chemical engineers are involved in the safe design of these facilities.

In some parts of the world, the extractive industries have caused long-term environmental pollution. There have been numerous examples of acid and metalliferous drainage from metal and coal mines poisoning soils and water; multiple concerns have been raised over gas fracking.

Chemical engineers play a role in embedding proactive process safety and environmental protection at all stages of resource extraction and manufacturing, from design and development to operation and decommissioning. At a higher level, chemical engineers are called upon to develop strategies to minimise and manage environmental impact. Chemical engineers play a vital role in long-term planning, risk assessments, and informing and adopting proper regulation and responsible practices.

**FACTS**

**Global production dropped 6.8% in 2020 during the COVID-19 pandemic [24] and while it rebounded in 2021, huge rises in energy costs are expected to impact production in 2022.**

**Global production and manufacturing sectors contribute 20% of global carbon emissions and consume 54% of the world's energy resources. [25]**

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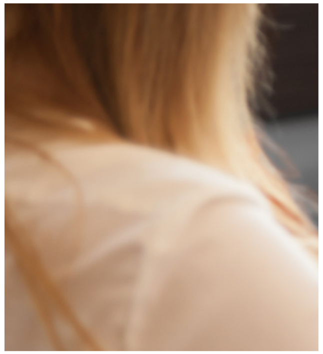

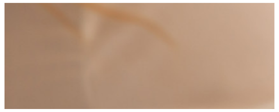

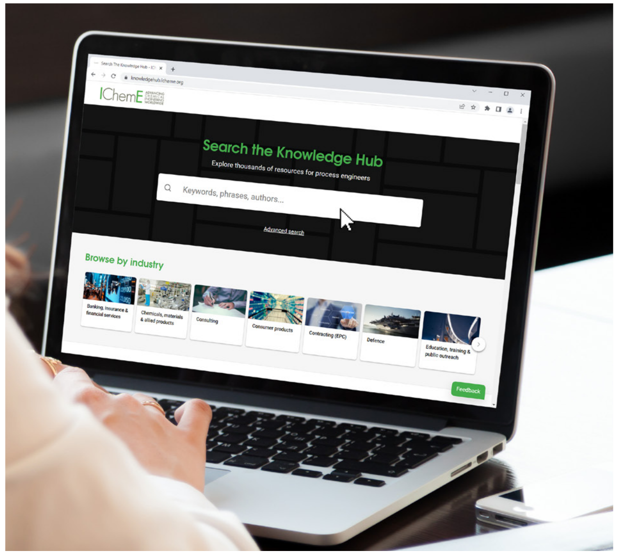



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# Further reading

**IChemE Strategy**
IChemE's current five-year strategy
www.icheme.org/strategy/

**Priority Topics**
Information and materials around IChemE's technical focus areas
www.icheme.org/knowledge/priority-topics/

**ChemEng Evolution**
Articles and webinars highlighting the impact of chemical engineering and the ideas and solutions being developed for the future
www.chemengevolution.org/

**Knowledge Hub**
Access to IChemE's journals, magazines and other written resources
www.icheme.org/knowledge/knowledge-hub/

**Sustainability Hub**
Information, online training and other materials relating to sustainability
www.icheme.org/knowledge/sustainability-hub/

**Contributions to policy issues**
IChemE's policy briefings and consultation responses
www.icheme.org/knowledge/policy/policy-briefings/contributions-to-policy-issues/

**IChemE Code of Professional Conduct**
Covers both the professional competence of members and their professional relationships
www.icheme.org/about-us/governance/code-of-professional-conduct/

**Engineering ethics resources**

UK Engineering Council Statement of Ethical Principles
www.engc.org.uk/professional-ethics

2022 Report on Engineering Ethics
www.engc.org.uk/media/3921/engineering-ethics-report-february-2022.pdf

**Diversity, Equality and Inclusion resources**

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# Where do I fit in?

*Chemical Engineering Matters* reflects the diverse opinions of IChemE's international membership. Particular emphasis has been placed on areas where chemical engineering has a significant global impact. The report has identified a series of strategic challenges and puts forward ideas on possible directions of travel for IChemE and the wider chemical engineering community. Readers can engage in the next stage of the conversation in several different ways:

- IChemE values feedback from its members on any of the issues raised in this report, but more importantly we urge you take advantage of free membership of our special interest groups (SIGs). The SIGs cover the wide range of topics found in *Chemical Engineering Matters* and provide a regular forum for technical discussion. They can also provide a platform for sharing new research thinking and the latest developments in industry. Please use this report to spark new ideas and set new priorities;
- if you are an employer, IChemE can connect you to a wide range of expertise related to many of the process solutions identified in this report. Chemical engineers can help you grow your business;
- this report will be used as a catalyst for discussion and co-operation with other disciplines. Proposals for collaboration around any of the topics raised are welcomed. Other engineers and scientists are invited to submit ideas for joint meetings and projects;
- if you are a policy-maker at local, national or international level or in the media, you will see that IChemE is an advocate for solutions that will support a safer and more sustainable world. If you think that our members can be a useful addition to your contact book, please get in touch;
- IChemE encourages all chemical engineers to identify the areas of the vistas where they can make an impact. Please share this report with others.

To continue the conversation contact: cem@icheme.org

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