Sustainable systems

Context

Chemical and process engineering activities are invariably part of wider interconnected systems, eg:

- **global value chains that source, transform, and distribute materials across locations and sectors;**
- **integrated manufacturing systems that use resources to transform materials;**
- **business systems interfacing with society, economic systems, and the environment.**

These systems extend to resources beyond the food – energy – water – waste nexus, timescales beyond millennia, and dimensions beyond the atmosphere. (This report does not explicitly consider activities such as space mining that extract resources from beyond the Earth.)

The systems affect the ecosystem, society, and economics through extraction, valorisation, and transport of material and energy resources. Value chains embed circularity to reduce cost, consumption of resources, and waste. Systems thinking, that links scientific disciplines, technology, ethics, policy, and regulations, is essential to enable sustainable consumption and production within resource limits and the environment's capacity.

Key technologies and areas of activity

The manufacture of products drives processing and production of (bio-)chemicals. As discussed in the section on process and product innovation, products with linear life cycles impede sustainability. That is, product design underpins sustainable systems. Creative and strategic R&D can promote sustainable systems for the circular economy.

Products and components need to be designed to enable recycling, including deconstruction, de-polymerisation, and de-alloying, so materials require careful selection too. Reuse and recycling can 'keep molecules in use for longer' and enable cross-sector valorisation and circular use of resources. In turn, less new material is used, waste is minimised, and fewer harmful enduring substances are released to the environment. Circular business models (eg products-as-a-service or leasing of chemicals or metals) reward sustainable product design. Conversely, current models produce consumer goods with short lives that are hard to repair; furthermore, in advanced economies, labour is costly, compared to resources.

Processes and plants producing chemicals and other products are complex and sit within complex value networks. Reducing waste at source by using materials more efficiently means reduced manufacturing costs, but requires systems thinking, careful planning and detailed understanding of production processes and how to improve them. Waste management aims to collect, sort, treat, recover, recycle, valorise, and safely dispose of waste, but adequate facilities are lacking, especially in low-income countries. Chemical engineers develop, design, operate, and optimise processes such as depolymerisation, metal extraction and refining, anaerobic digestion, and precipitation.

Efficient, integrated systems for generating, storing, and transmitting electrical and thermal energy can avoid greenhouse gas emissions. Decarbonised, cost-effective thermal energy technologies are expected to play an important role. Systems of various scales support production of electricity from renewable energy sources.

Especially for larger molecules, production systems that integrate engineering biology and process engineering present opportunities and challenges. Likewise, systems integrating nature-based solutions into value chains (eg in the food, drink, and water sectors) can reduce emissions, pollution, and water scarcity. Effective interdisciplinary systems thinking can help identify production approaches that promote biodiversity, that conserve and redress damage to the natural environment, or that apply appropriate technologies.

Challenges and constraints

Designing products for sustainability is challenging: circularity needs to be designed in to products and services, production processes, and business models at the outset. Discerning technology development can maximise benefit and avoid wasting time and resources. Product design must consider why (or whether) a product is needed, who will use it, how it will be manufactured, at what scale, with what by-products, and the consequences of manufacturing and using it. In addition, end-of-useful-life issues arise: what useful lifetime is expected; how a product or component will be recycled, reused or made useful; the social, environmental, and economic impacts of (bio)degradation and disposal. Tools are needed to support eliminate – reuse – reduce practices (analogous to those for inherently safer design), in preference to applying end-of-pipe solutions. As one member put it – "We need the equivalent of Trevor Kletz for sustainability."

Sustainable production depends on efficient use and reuse of systems of supporting assets, including processing units, infrastructure for waste management, providing water and energy, logistics, and land. Stranded assets – assets that stop operating prematurely – represent very significant financial liabilities: associated physical, financial and social risks demand careful, systematic management.

Life cycle analysis frameworks, with their multiple impact categories, help to account appropriately for techno-economic, social, and environmental dimensions of sustainability. Systematically applying and interpreting these frameworks, while considering the overall system, is a challenge that requires considerable experience and extensive datasets. Decarbonisation has a narrower scope but presents similar challenges.

Chemical and process engineering contributions and skills

Systems for sustainable development are large, in terms of complexity, dimensions, and timescales. Chemical engineers and their systems-thinking skills are well placed to exploit interactions and trade-offs within these systems. Practical problem-solving and comprehensive understanding of long-term life cycles are essential. Chemical engineers with project management skills can help to integrate sustainability when building and retrofitting complex processing facilities.

Well-managed multi-disciplinary teams boost development and implementation of safe and sustainable production processes. These teams apply engineering and science, and account for environmental, business, economic, and regulatory issues, as well as regional and societal dimensions. Chemical engineers need strong scientific foundations and skills to work in such teams.

Chemical engineers' understanding of life cycle assessment frameworks – and assumptions, limitations and applicability – and their skills for product, process, and system design and modelling are valuable. Digital tools, including those applying first-principles models, machine learning, augmented and artificial intelligence, digital twins, and big data are useful for design, operation, automation, and control of process systems, if chemical engineers apply them effectively and safely. Relevant experience of operational and practical issues, including scheduling, planning, control, and supply chain management, also informs and enhances chemical engineers' activities.

Chemical engineers can inform development of regulatory frameworks to advance, rather than hinder, development of sustainable systems. Their systems-thinking skills can positively influence policy and practice (eg accounting for emissions, impact assessment, investment criteria for systems), and shape attitudes to enable full life cycle perspectives on products and their environmental impacts. Advocacy and thought leadership can help integrate sustainable systems thinking into chemical engineering practice and raise awareness and understanding across wider society about the benefits, downsides, and trade-offs associated with proposed sustainable systems solutions or approaches.