The role of chemists and chemical engineers in a sustainable world

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**The world at a crossroads**

There has never been a better time to be starting on a career in chemistry or chemical engineering. Sometimes we hear negative sentiments such as “I want my country to be a chemical free zone” (Scandinavian Government Minister); “Chemistry is a mature discipline; there is nothing else to do”; “All chemistry can be done by computers now. Take your lab coat off!”, “Everything is biotechnology now; there is nothing left for chemistry”. However, he world is at a crossroads where we come from a time where we used fossil fuels, which are running out and causing global climate change, and precious elements, which are in short supply, in a linear use and discard economy causing massive problems of waste and resource depletion. We must turn to a time where we use renewable resources, taking care not to compete with food production, and earth abundant elements. We must use them in a circular economy where everything is used for longer, reused, repaired and eventually fully recycled. Only if we do this can our children and their descendants continue to enjoy the diverse and beautiful world that is has been our good fortune to inhabit. This transformation, which is urgent, will have new chemistry and chemical engineering processes at the forefront. There is so much to discover and to implement and it must be done quickly.

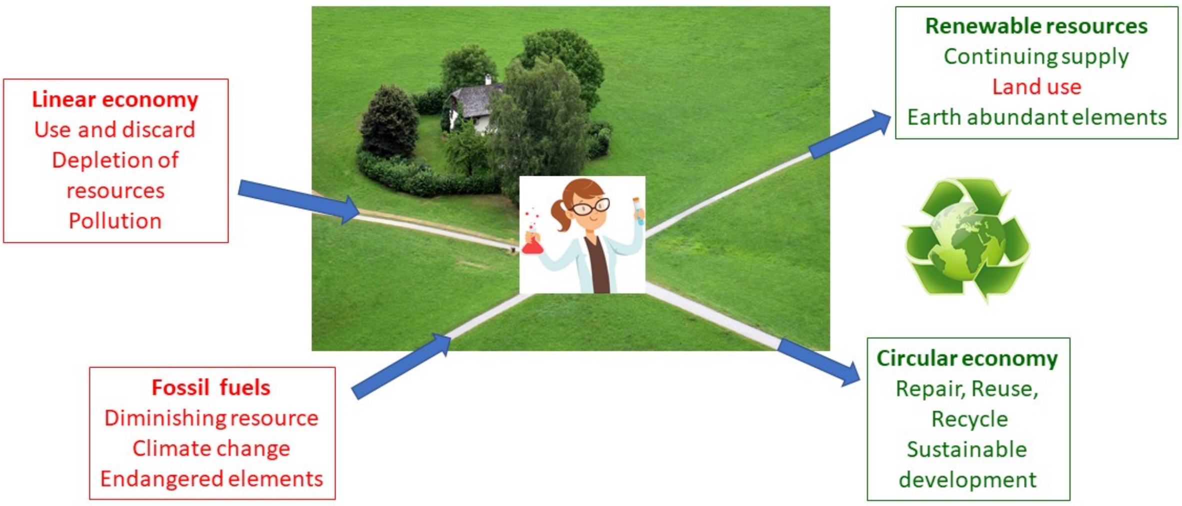


**Fig 1** The world is at a crossroads coming from the linear economy and depleting resources but going to a circular economy based on renewable resources. Chemists and Chemical Engineers will direct the way to the future. Crossroads image by Manfred Antranias Zimmer from Pixabay; central figure reproduced with permission from www.canstockphoto.com

The United Nations has identified a road map to this sustainable world which involves 17 sustainability development goals.[1] Their thesis is:

> *“The Sustainable Development Goals are the blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace and justice. The 17 Goals are all*

*interconnected, and in order to leave no one behind, it is important that we achieve them all by 2030."*

(reproduced directly from https://www.un.org/sustainabledevelopment/sustainable-development-goals/ )

Achieving almost all of this requires major input from chemists and chemical engineers. Let's look at what we have to offer.

**Goal 2 – Zero hunger**

Agrochemicals (fertilisers, weed-killers and pesticides) enhance crop production by up to 50 %.[2] Since we produce approximately the amount of food needed to feed the world's population, although some people have too little and others too much, it follows that around 2-3 billion extra people are able to be fed because of the positive effect of agrochemicals. Agrochemicals must be highly active (only small amounts used), highly specific (only having the required effect and only in the desired place) and non-toxic (if they enter the food chain, they must be benign). Many chemicals having all of these properties are available but some are threatened with a ban without a full risk-benefit analysis being carried out. The recent attempt to ban the use of glyphosate in Europe fell into this category. Surely it is better for a farmer to wear protective gear rather than for a highly effective and otherwise benign chemical to be banned only because it might harm farmers who do not use such clothing?

The fertiliser ammonia, made from nitrogen and hydrogen in the Haber-Bosch process is the most produced man-made chemical at 200 million tonnes per annum (tpa) and is the main contributor to increased crop yield.[3] So much has been used that > 50 % of the nitrogen in our bodies has gone through this process.[3] It is a highly optimised process yet it uses 1-2 % of the world's energy supply,[4] equivalent to the total energy consumption of 100,000 people. It also consumes 5 % of all methane[4] to produce energy and the hydrogen required for the process, throwing all the carbon away as $CO_2$, sometimes after its being held up in urea one of the active fertiliser forms.[5] The main problems are the activity of the catalyst and the negative entropy change of the process. The latter favours working at low temperature whilst high rates can only be achieved at high temperature. This means that the conversion per pass is low. Alwin Mittasch tested over1,000 different catalyst compositions,[6]so catalyst improvements are unlikely, but it may be possible to heat differentially the catalyst so that the rate is high whilst keeping the flowing stream cool so the equilibrium position is improved..[7] Even tiny improvements could have a massive effect on reducing energy utilisation. As we move towards cheap renewable energy, hydrogen production from water electrolysis would be the ideal method for making the hydrogen for ammonia synthesis, saving almost all of the $CO_2$ emissions. More efficient electrolysers using earth abundant elements in the electrodes must be the target here and already progress is being made by using magnetic heating of the electrodes in cool water.[8]

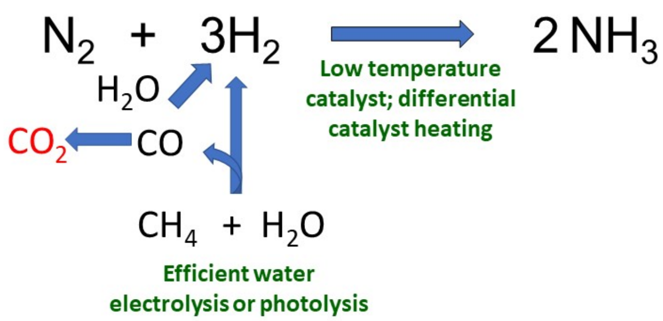


**Fig 2** The Haber process for the synthesis of fertiliser ammonia allows us to feed 2 bn extra people but uses 1-2 % of the world's energy and 5 % of world methane. In green are suggestions for improving this essential process.

**Goal 3 – Good Health and wellbeing**
Tackling antibiotic resistant organisms, ameliorating diseases of ageing (dementia, Parkinson's disease, many cancers) and lifestyle diseases (obesity, diabetes, drug and alcohol abuse) will require many new kinds of medicines. These will be made by chemists and commercialised by chemical engineers. The 2018 Nobel Prize for Chemistry was won by Frances Arnold, George Smith and Gregory Winter for using directed evolution of proteins to produce new drugs. 60% of all new drugs are made in this way, which uses extensive chemistry.[9]

**Goal 4 – Quality Education**
Chemical education throughout the world is generally of very high quality at school and University level. The skills of a chemistry graduate are much in demand not only for employment in chemistry but in many sectors where analytical thinking is required. However, one area which is afforded little attention in chemical education is ethics. That is why the *European Chemical Society* (EuChemS) through Jan Mehlich has developed an on-line course, *Good chemistry – methodological, ethical, and social dimensions*[10] consisting of 16 x 45 minute videos with quizzes, case studies, assignments and assessments. Such a course should be a prerequisite for working in any chemical or other scientific environment.

**Goal 5 – Gender Equality**
Surveys in many countries show that, although almost equal numbers of men and women take chemistry undergraduate programmes, only about 30 % of the workforce in the chemical industry are women. In academia, the situation is worse with only 9 % of chemistry full Professors being women.[11] The is even poorer involvement of women in chemical engineering. We are losing a huge talent pool because of the "leaky pipeline". We must change the culture, the working hours, child care and the handling of maternity leave so as to make our wonderful subject attractive and accessible to all.[12]

**Goal 6 – Clean Water and Sanitation**
2000 children die each day because they do not have access to clean water.[13] That is equivalent to the whole population of a city the size of Frankfurt dying within 1 year. In many countries having ready access to cheap chlorine allows for safe purification of water. However, a chlorine cylinder placed in a dustbin of high explosives and thrown from a helicopter becomes a banned chemical weapon. Dual use of chemicals is a serious problem so the development of new water purification processes that can be carried out in remote places is essential. Sophisticated processes such as using photoexcitation of $TiO_2$ with sunlight to generate hydroxide radicals that destroy pollutants[14] will have their place, but many other possibilities urgently await the enquiring mind.

**Goals 7 – Affordable and Clean Energy and 13 – Climate Action**
The provision of clean energy and climate action are intimately linked. At 10 % conversion, the sun shining on an area approximately equivalent to that of Libya provides enough energy for all the current requirements of the world. It is the only source of energy coming into the earth so we must harness it more effectively than we currently do. Biomass, wind, wave, hydro are all ways of converting solar energy to electricity, and more recently we have introduced photovoltaics to this list. These must all be expanded and the conversion made more efficient with chemists and chemical engineers taking the lead. Hydrogen could be an ideal fuel. It burns only to make water and it can be produced from water by electrolysis or perhaps direct photolysis using sunlight. Direct photolysis has typically been rather inefficient, but a system based on Earth-

abundant elements achieved 7.9 % conversion efficiency in 2011.[15] The lifetime is insufficient for commercialisation, but it shows that it can be done and more work is required.

Handling and storing hydrogen is another challenge, whether it be stored through physical adsorption or reversible chemical complexation. Significant further progress is required in this fascinating area. Older readers will remember using "Town gas" in stoves for heating and cooking – It is still used in Hong Kong. Town gas contains 50 % hydrogen. It was stored in gasometers and distributed through pipes so, despite its explosive nature, we know how to distribute and use it safely.

Although it is relatively easy for developed nations to move entirely to renewable energy, we start from a position where we have learnt from extensively using fossil fuels. When we realise that the US uses 17 % of the world's energy for 4 % of the world's population whilst India with 17 % of the world population uses 6 % of world energy,[16] it is incumbent upon the developed world not only to reduce consumption but also to facilitate the development of other nations quickly and sustainably without passing through a period of massive fossil fuel use .


**Goals 9 – Industrial Innovation and Infrastructure, 11 – Sustainable Cities and Communities and 12 – Responsible Consumption and Production**

Our attitude towards the way we make and use consumer items will have to change. Currently, far too often we make an item for consumer use and build in redundancy so that when one part breaks, for example the lock on a dishwasher, we are advised to buy a new machine and the old one is discarded. This is an example of the linear economy and it suffers from two huge problems. Firstly, it consumes raw materials sometimes at an unsustainable rate and secondly, it produces huge amounts of waste. We shall have to move very quickly towards the circular economy where we manufacture objects to last, we use them for longer, we replace or repair parts that break down, we reuse them in whole or in part and, when eventually the object has come to the end of its useful life, we recycle as many of the elements in it as possible. Here, waste becomes a raw material and we move away from both element depletion and waste accumulation.

As part of the celebrations of the UNESCO proclaimed *International Year of the Periodic Table* (2019) the *European Chemical Society* (EuChemS) has released a new version of the Periodic Table highlighting element availability and vulnerability towards dispersion.[17] It also highlights which elements can come from conflict minerals and 31 elements that are in smart phones. All the elements that can come from conflict minerals are in smart phones and 6 of the elements in smart phones are expected to be depleted within 100 years if we carry on as we are. Smartphones are the archetypal use and discard technology, often being replaced every 2-3 years.

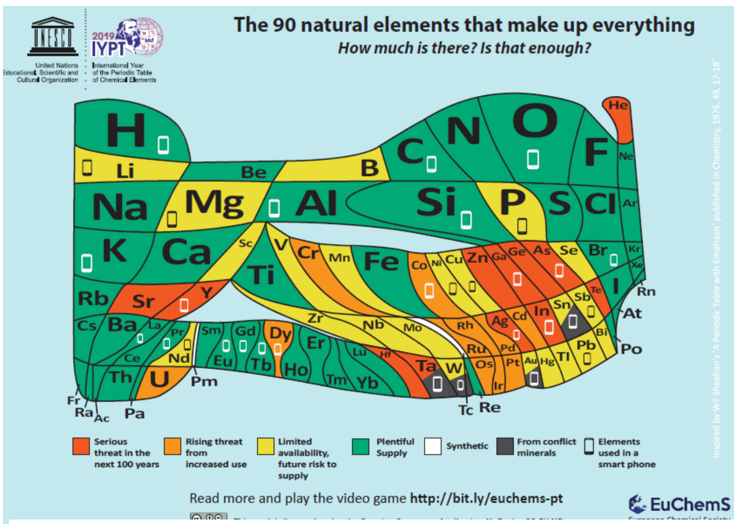


**Fig 3** Periodic Table released by the European Chemical Society to celebrate the *International Year of the Periodic Table* featuring element availability and vulnerability as well as elements that can come from conflict zones and those in smart phones. Downloaded from http://bit,ly/euchems-pt

Indeed 10 M smartphones are exchanged in Europe **every month**.[18] The situation here is even worse because very many of these phones are not traded in but kept in drawers or cupboards. The elements in these phones are beyond reach for recycling. In a recent survey the Royal Society of Chemistry (RSC)[19] found that 51 % of all homes in the UK have at least one unused piece of electronic equipment and 42 % have more than 5. For those phones that are handed in there are not enough ethical recycling facilities available so they go to the developing world, sometimes for reuse but then to be "mined" for their gold, often by children using strong acids in the streets with phone carcasses piled high beside the road and pools of toxic acidic residues developing. The whole situation is encouraged by manufactures making replacement of parts in smart phones very difficult through using very strong glues and specialised screws for which most people do not have appropriate tools.

The RSC concludes its survey by proposing:

- Retailers will need to introduce take-back schemes – where people can be assured that their data will be securely wiped, and their devices will be efficiently recycled
- Manufacturers will need to build repairability and recyclability into designs from the beginning, and
- Governments will need to provide consistent guidelines and infrastructure to facilitate a circular economy

I would add that you should keep you phone for longer.

There are great opportunities for chemists and chemical engineers in recycling genuinely end-of-life goods. Our track record on recycling any but the rarest elements is poor.

It is not just electronic goods that are a problem. Look around you; almost everything you see has been made in the chemical industry mostly from depleting fossil fuels. Continuing to have all paints flooring, surface coverings, plastics, many clothes etc will require a complete reinvention of the chemical industry. We shall have to use new feedstocks which we grow but are not in competition with food for land use. The two major opportunities come through lignin, from the woodier parts of plants and cellulose from the greener parts. Both are highly crosslinked complex polymers so obtaining pure single products from them will be very challenging but also highly rewarding. These studies are in their infancy but new processes are beginning to be developed. [20]

Whereas current processes in the chemical industry often involve putting oxygen and nitrogen into hydrocarbons, the new industry will involve reductive chemistry – removing oxygen from the natural resources. A whole new world of reagents awaits exploration. This chemistry must also be done differently from the stoichiometric or high energy reactions of today. To minimise waste, pollution and energy use, the 12 principles of green chemistry[21] must be applied together with full life cycle analyses. Again, we are just starting to scratch the surface of what can be done. Easier chemistry can be carried out on abundant natural oils, but again, competition with food must be avoided. Some oils such as castor oil (inedible), "tall oil" from paper manufacturing (a mixture of unsaturated $C_{18}$ carboxylic acids)[22] or cashew nut shell liquid (mildly toxic side product of cashew processing containing phenols bearing a $C_{15}$ chain in the 3-position)[23] , are all available at $\geq$ 1 million tpa and provide interesting substrates for elaboration.

**13 – Climate Action**

To ensure that global warming can be controlled, it is probably not sufficient just to stop using fossil fuels, especially with the disparity in per capita energy use. We shall need to extract $CO_2$ from the air and use or store it safely. This will be a major undertaking with $CO_2$ present at only 400 ppm; too much for the climate but very dilute for extraction. Prototypes are being built and tested[24] although the viability of such approaches has been questioned on the basis that only small percentages can be used in this way. [25] More creative thinking is now required urgently. Although the concentration is low, the amount of $CO_2$ that will have to be removed is huge. As of yet, we don't really know what to do with it. However, clearing forests without replanting schemes will quickly make the problem even more urgent.


**Goals 14 – Life Below Water and 15 – Life on land**

Life in all its forms depends upon a clean and vibrant ecosystem. We simply cannot continue to pour our waste into the land and the sea. We grow plants, which we eat either directly or through animals that have eaten them. All the nutrients then end up in human bodies and mostly in human excrement which, after treatment, is flushed into the sea. We then have to replenish the land using fertilisers - another classical example of the linear economy. There are big opportunities in recovering elements such as phosphorus from human excrement.[26]

All around us we see plastics. In many cases they are wonder materials with unique properties. Polyethylene gas pipes and Perspex windows are just two examples. But we have abused plastics through our thoughtless, reckless linear economy so that the land and the seas are heavily polluted. We will stop single-use plastics, but we still need to have good ways of dealing with end of use plastics. All plastic objects should be reusable and recyclable. Some may be biodegradable, but even then they can do untold damage in the period when biodegradation is happening so they should not be allowed into the wider biosphere. Some of our current plastics will be replaced by paper, wood and other bioderived materials, but there will be a large opportunity to design new polymers for specific tasks with their full lifecycle being taken not account.


**Goals 17 – Partnerships for the Goals**

I have argued that chemists and chemical engineers hold the keys to a future sustainable world, but they will not be able to do it alone. They must work with experts from disciplines as diverse as agriculture and sociology, psychology and politics, not to mention all the other branches of science and engineering. We currently carry out risk assessments of everything we plan to do in the lab to protect ourselves and our co-workers but the time has come where we need to take a much wider view about the long term consequences of what we propose and to initiate discussions before we start with possible end users, the public and experts from so many other disciplines.


**Goals 1 – No Poverty, 8 – Decent Work and Economic Growth, 10 – Reduced Inequalities and 16 – Peace and Justice, Strong Institutions**

What then of the four goals that do not have a direct input from chemists and chemical engineers? I would argue that, if we accept the challenges laid down in this article and many others, realising that their successful completion will reap huge benefits to those who have been involved in the discoveries and their implementation as well as for the whole world, then the four goals of "no poverty", "decent work and economic growth", "reduced inequalities" and "peace and justice" will automatically fall into place, provided that everyone sees the benefit to themselves of helping everyone else in our beautiful and diverse world.

If we fail to tackle the huge potential problem of climate change and do not build a sustainable world economy, poverty, inequality, economic stagnation and conflict will all grow towards the destruction of the world as we know it.

The future is bright – the future lies in the hands of chemists and chemical engineers.

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[1] *United Nations* **2015**, https://www.un.org/sustainabledevelopment/.

[2] V. Seufert, N. Ramankutty, J. A. Foley, *Nature* **2012**, *485*, 229-232.

[3] V. Smil, *Global Biogeochemical Cycles* **1999**, *13*, 647-662.

[4] *WayBackMachine, Fertiliser Indicators* **2002**, https://web.archive.org/web/20080424083111/http://www.fertilizer.org/ifa/statistics/indicators/ind_reserves.asp.

[5] C. Egenhofer, L. Schrefler, V. Rizos, F. Infelise, G. Luchetta, F. Simonelli, W. Stoefs, J. Timini, L. Colantoni, *Centre for European Policy Studies; Ammonia Impact Assessment* **2014**, ENTR/2008/2006 LOT 2004.

[6] R. E. Oesper, *J. Chem. Educ.* **1948**, *25*, 531.

[7] aW. Wang, G. Tuci, D. V. Cuong, Y. F. Liu, A. Rossin, L. Luconi, J. M. Nhut, N. D. Lam, P. H. Cuong, G. Giambastiani, *Acs Catalysis* **2019**, *9*, 7921-7935; bA. Bordet, L. M. Lacroix, P. F. Fazzini, J. Carrey, K. Soulantica, B. Chaudret, *Angew. Chem. Int. Ed.* **2016**, *55*, 15894-15898.

[8] aC. Niether, S. Faure, A. Bordet, J. Deseure, M. Chatenet, J. Carrey, B. Chaudret, A. Rouet, *Nature Energy* **2018**, *3*, 476-483; bF. A. Garces-Pineda, M. Blasco-Ahicart, D. Nieto-Castro, N. Lopez, J. R. Galan-Mascaros, *Nature Energy* **2019**, *4*, 519-525.

[9] aF. H. Arnold, *Angew. Chem. Int. Ed.* **2019**, *58*, 14420-14426; bG. P. Smith, *Angew. Chem. Int. Ed.* **2019**, *58*, 14428-14437; cG. Winter, *Angew. Chem. Int. Ed.* **2019**, *58*, 14438-14445.

[10] *European Chemical Society* **2018**, Available through www.euchems.eu.

[11] *Royal Society of Chemistry Diversity Landscape of the Chemical Sciences* **2018**, https://www.rsc.org/globalassets/02-about-us/our-strategy/inclusion-diversity/cm-044-017_a044-diversity-landscape-of-the-chemical-sciences-report_web-042.pdf.

[12] *Royal Society of Chemistry, Breaking the Barriers* **2019**, https://www.rsc.org/campaigning-outreach/campaigning/incldiv/inclusion--diversity-resources/womens-progression/.

[13] *UNICEF* **2019**, https://news.un.org/en/story/2019/2003/1035171.

[14] K. Wetchakun, N. Wetchakun, S. Sakulsermsuk, *Journal of Industrial and Engineering Chemistry* **2019**, *71*, 19-49.

[15] S. Y. Reece, J. A. Hamel, K. Sung, T. D. Jarvi, A. J. Esswein, J. J. H. Pijpers, D. G. Nocera, *Science* **2011**, *334*, 645-648.

[16] *BP Statistical Review of World Energy* **2019**, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf.

[17] *European Chemical Society, Element Scarcity Periodic Table* **2019**, https://www.euchems.eu/euchems-periodic-table/.

[18] M. Polak, L. Drapalova, *Waste Management* **2012**, *32*, 1583-1591.

[19] *Royal Society of Chemistry, Elements in Danger* **2019**, https://www.rsc.org/campaigning-outreach/campaigning/saving-precious-elements/elements-in-danger/.
[20] S. J. Liu, L. C. Bai, A. P. van Muyden, Z. J. Huang, X. J. Cui, Z. F. Fei, X. H. Li, X. L. Hu, P. J. Dyson, *Green Chem.* **2019**, *21*, 1974-1981.
[21] P. T. Anastas, M. M. Kirchhoff, *Accounts Chem. Res.* **2002**, *35*, 686-694.
[22] M. R. L. Furst, T. Seidensticker, D. J. Cole-Hamilton, *Green Chem.* **2013**, *15*, 1218-1225.
[23] Y. P. Shi, P. C. J. Kamer, D. J. Cole-Hamilton, *Green Chem.* **2019**, *21*, 1043-1053.
[24] D. P. Hanak, B. G. Jenkins, T. Kruger, V. Manovic, *Applied Energy* **2017**, *205*, 1189-1201.
[25] N. Mac Dowell, P. S. Fennell, N. Shah, G. C. Maitland, *Nature Climate Change* **2017**, *7*, 243-249.
[26] aR. Harder, R. Wielemaker, T. A. Larsen, G. Zeeman, G. Öberg, *Critical Reviews in Environmental Science and Technology* **2019**, *49*, 695-743; bJ. R. Mihelcic, L. M. Fry, R. Shaw, *Chemosphere* **2011**, *84*, 832-839.