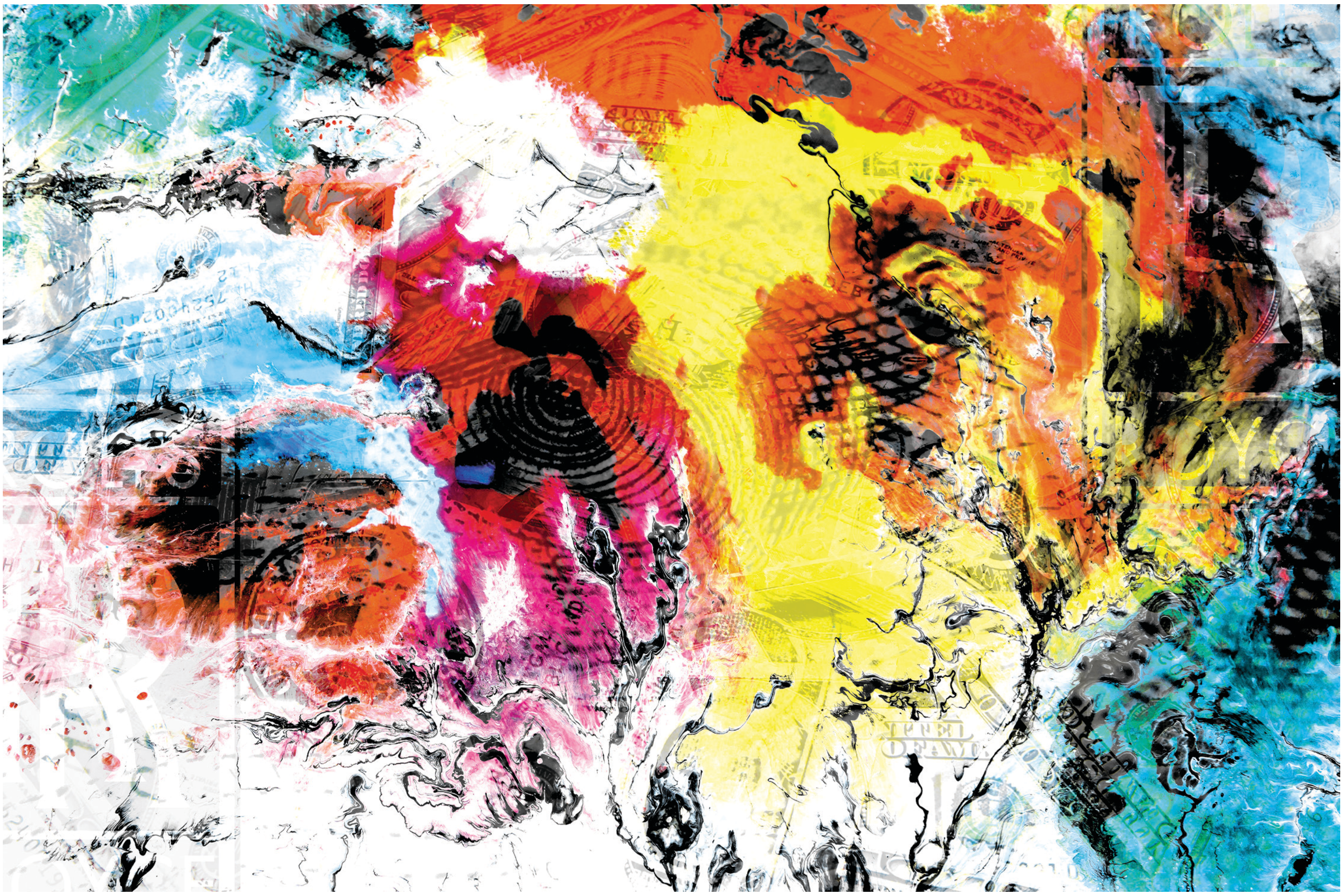
S218_1

Sustainable chemistry



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Introduction

This free course will look at how chemists play an increasingly crucial role in ensuring a sustainable future for the planet.

By focussing on the large scale production ammonia, one of the most important industrial chemicals, you will look at how chemists are leading the development of new manufacturing processes that use chemicals more efficiently, and in a less polluting way, together with greater use of recycling. You will look at how the principles of 'green chemistry' may be adopted to make chemicals and chemical-based products whilst minimising any detrimental impact on the environment.

In addition, sustainable use of resources and raw materials must be considered too. As such you will look at the chemical elements, in particular those that are likely to be in short supply in the future and what steps must be taken to ensure they are not lost forever.

Glossary

Chemical terms are highlighted in bold when they appear within the text, and a brief definition is provided when clicking on the word, as well as within a glossary at the end of the course.

This OpenLearn course is an adapted extract from the Open University course S218 *Concepts in chemistry*.

Learning outcomes

After studying this course you should be able to:

- recognise how chemists can play a role in achieving the United Nations Sustainable Development Goals and helping to ensure a sustainable future for the planet
- understand the difference between linear and circular economies
- appreciate the challenges facing chemists when manufacturing chemicals on a large scale
- understand what is meant by 'green chemistry' and 'atom economy'
- identify endangered elements in the Periodic Table.

1 Chemistry and chemical manufacture – negative perceptions

There is no doubt chemistry, and its vast associated manufacturing industry is crucial for our existence – from food production to pharmaceuticals; andfrom modern materials to the cleaning products we find in our homes.

Chemistry and the chemical industry is often viewed in a poor light. But why?

Chemical manufacture is often perceived as being polluting and a major cause of damage to our environment. And indeed for many years that was the definitely the case (Figure 1)

Figure 1 The chemical industry is often viewed as a major source of pollution and environmental damage.

2 Circular economies

There is currently a drive to transition from a traditional linear economy to a circular model in which the latter maximises the use of renewable resources (more on this in Video 1 in the next section.).

These models are summarised in Figure 2.

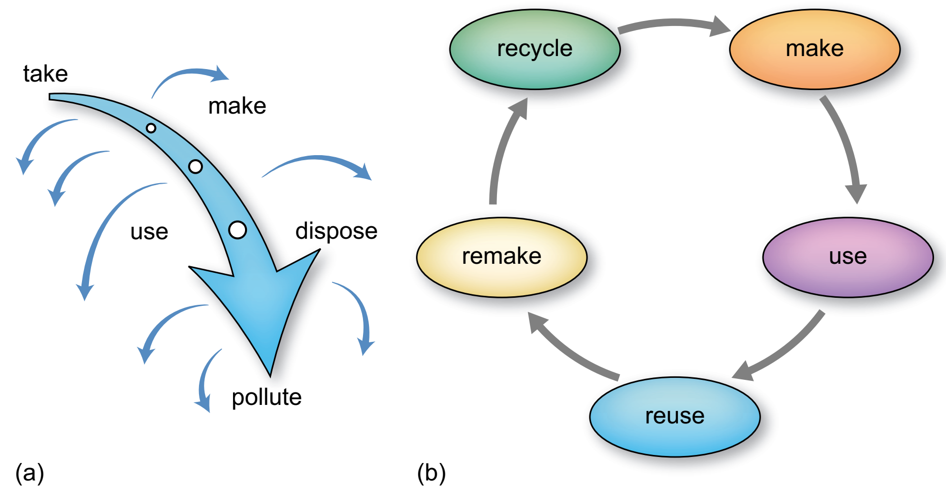


Figure 2(a) Linear and (b) circular economies

- What are the main differences between a linear and circular economy?
- In the linear approach, goods are produced and then thrown away – often in landfill. The circular economy involves treating waste as a raw material for the production of new goods. This extends to recycling and reusing products where possible.

One material that exemplifies the need to move to a circular economy is plastic – this is the focus of the next section.

2.1 Plastic and the circular economy

There's no doubt plastic is vital to our everyday lives. But if thrown away, many plastics take hundreds of years to break down.. One positive aspect of moving towards a circular approach would means less waste plastic would end up in landfill or our environment.

In fact it is the unique properties of plastic itself that helps us keep it in use as long as possible. This is discussed in the following video.

Video content is not available in this format.

Video 1 How to solve the plastic problem (video: ©The Open University and BBC)

3 UN Sustainable Development Goals

In 2015 the United Nations (UN) introduced 17 wide ranging globally agreed objectives– Sustainable Development Goals (SDGs), aimed at ending poverty, protecting the planet and ensuring prosperity for all. The aim is to achieve these targets by 2030. See Video 2 below.

Video content is not available in this format.

Video 2UN SDGs. (This video has no narration.)

The circular economy approach you saw in Section 2 is in line with the United Nations (UN) Sustainable Development Goal (SDG) 12, ‘Responsible consumption and production’.

And in the next two sections you’ll be looking at two further UN goals that are of particular relevance to chemists:

- SDG 2, ‘Zero hunger’, and
- SDG 7, ‘Affordable and clean energy’.

3.1 UN Sustainable Development Goals in practice: zero hunger

One of the most important industrial chemicals is ammonia (represented by the **chemical formula**, NH_3).

Ammonia is prepared, on a massive scale using the Haber–Bosch process.

The chemistry at the heart of the Haber-Bosch process is the reaction of two gases, nitrogen and hydrogen, which may be represented by the following **chemical equation**.

$$N_2 + 3H_2 \rightarrow 2NH_3 \quad \textbf{(1)}$$

But why is this reaction so important in the context of the SDG 2? Video 3 in the activity below provides some answers.

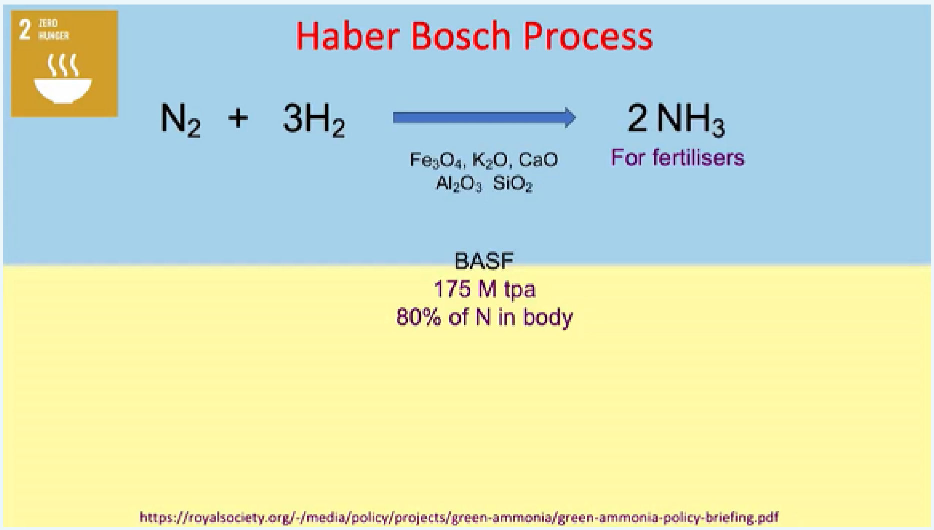
Activity 1 The Haber–Bosch process

Allow about 10 minutes

Watch the video and then answer the question that follows.

Video content is not available in this format.

Video 3 The Haber–Bosch process (video: ©The Open University)



Professor Cole-Hamilton refers to the Haber-Bosch process as the 'most important chemical reaction in the world'. How does he justify this statement?

Answer

Ammonia is essential for production of agricultural fertilisers essential for feeding the world's population. Fertilisers are used to make plant protein, which we either eat directly, or via animals – in fact 80% of the nitrogen in our bodies originates from industrially produced ammonia.

As discussed in Video 3, a chemical balancing act is required when selecting the ideal conditions for this reaction. So, let's summarise the challenges faced by chemists.

Challenges faced by chemists

As a general rule chemical reactions go faster as the temperature is raised. High temperatures do indeed increase reaction rate, but they also favour the reverse reaction which sees ammonia being converted back into nitrogen and hydrogen.

So, as discussed in Video 3, on balance, a moderate temperature with the addition of a **catalyst** and operating at high pressures is the preferred option.

But that's not all.

You also learned the production of ammonia is incredibly energy intensive, the main reason for this lies with one of the raw materials – hydrogen, The other feedstock, nitrogen, isn't a problem, there's plenty of it available in the air, but as described in Video 2 hydrogen has to be prepared by a chemical reaction on a vast scale which is hugely costly in terms of its energy requirement.

- The synthesis of hydrogen also has another drawback, detrimental to the environment. What is this?
- Methane, the source of hydrogen has the chemical formula CH_4, comprising one atom of carbon and four atoms of hydrogen. The problem is that in industrial scale chemical reactions used to produce hydrogen, *all* the carbon in methane is converted to huge amounts of carbon dioxide.

- How can chemists contribute to reducing the environmental impact of the Haber–Bosch process?
- By developing different approaches to hydrogen production and new **catalysts** for the reaction.

3.2 Affordable and clean energy

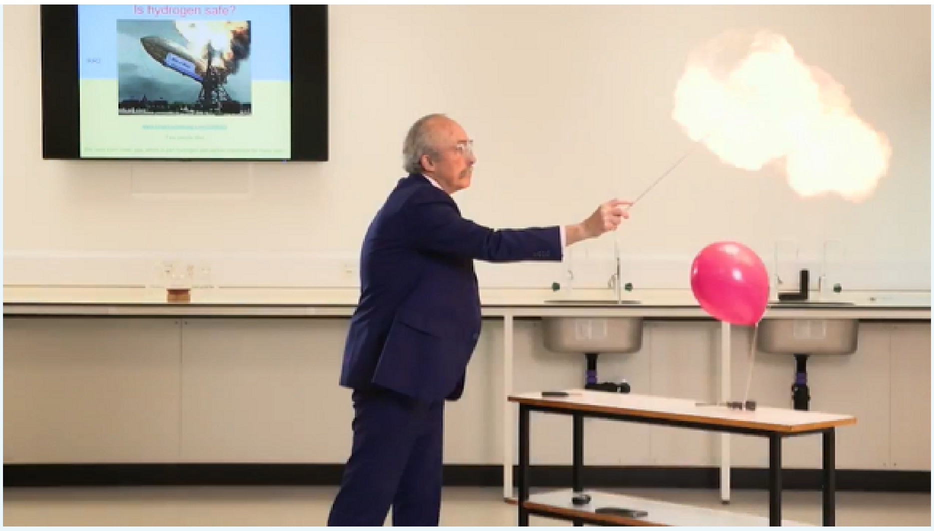
You'll now look at another UN SDG; this time number 7, 'Affordable and clean energy'.

Activity 2 Generating clean energy

Allow about 15 minutes

In the clip below you will look at the vital role of the Sun in generating clean energy, and how hydrogen is, and will be an important fuel moving forward. Then answer the two questions that follow.

Video content is not available in this format.
Video 4 Affordable and clean energy (video: ©The Open University)



Select the types of hydrogen from the given definitions.

Interactive content is not available in this format.

Why are new **electrode** materials required for **electrolysis** of water?

Answer

Currently electrodes are based on metals that are relatively scarce on Earth (e.g. platinum and iridium), so large scale application of this technology will require electrodes based on more abundant (and cheaper) materials.

4 Introducing green chemistry

In the 1990s, American chemists Paul Anastas and John Warner introduced the concept of green chemistry. Green chemistry is a set of twelve principles that view industrial scale chemical production in an environmentally sustainable, and economically viable way. In fact the principles are equally applicable to the chemist working in the laboratory.

Section 4.2 will look at the application of these principles but first you'll consider an important indicator of the efficiency of a chemical reaction, in other words how successful a reaction is at converting **reactants** to **products**, with as little waste as possible.

4.1 Atom Economy – quantifying waste in chemical reactions

One way of gauging the efficiency of a chemical manufacturing process and hence its environmental impact is to determine the atom economy for the reaction.

Atom economy– expressed as a percentage– is a sustainability metric that considers every chemical used in a chemical reaction, and the extent to which each is incorporated into the **product**.

To calculate atom economy, you start from a balanced chemical equation and determine how many atoms of **reactant** are incorporated into the product, and how many end up as by-products or waste.

The atom economy of a process is quantified by the following formula:

$$\%\ \text{atom economy} = \frac{\text{formula mass of product}}{\text{sum of reactant formula masses}} \times 100\% \qquad (2)$$

Where the formula mass of a substance is the sum of the average relative atomic masses of each atom in the **chemical formula**.

The higher the atom economy, the more efficient is the chemical manufacturing process, and the less waste is produced.

4.1.1 Calculating atom economy – an example

Let's consider 2-phenyl propane, an **organic compound** used in the synthesis of polymers and resins.

2-phenylpropane may be prepared by the reaction between benzene and 2-chloropropane (Figure 3).

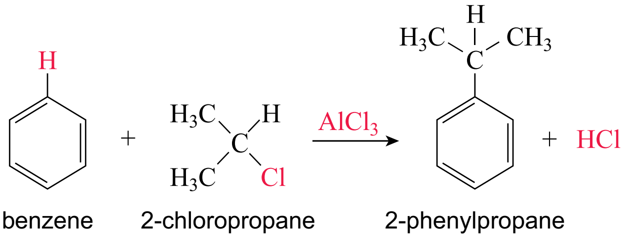


Figure 3 Synthesis of 2-phenylpropane. Atoms not used in product are shown in red.

Aluminium chloride ($AlCl_3$) is the **catalyst** for this reaction.

As a general rule **catalysts** are unchanged in a chemical reaction.

This is indeed the case for $AlCl_3$ but it remains in **solution** after the reaction and is difficult to recover. So in this particular case the **catalyst** has to be considered alongside the other reactants when calculating atom economy.

Activity 3 Calculating atom economy for the synthesis of 2 phenylpropane

Allow about 10 minutes

Let's work though the calculation of the atom economy of the reaction shown in Figure 3.To do this you will need to know the **relative atomic masses** of carbon (12.0), hydrogen (1.0), chlorine (35.5) and aluminium (27.0).

- Looking back at equation **(2)** what will be your first step in the calculation?

Answer

Looking back at the equation for atom economy given in Section 4.1, you need to start by working out the formula masses of your reactants and products.

Remember you are including $AlCl_3$ in this case.

These are as follows:

2 chloropropane: (3 x 12 g) + 35.5 g + 7.0 g = 78.5 g

Benzene: (6 x 12g) + (6 x 1) = 78 g

$AlCl_3$: 27.0 g + (3 x 35.5) = 133.5 g

2-phenylpropane: (9 x 12.0 g) + (12.0 x 1 g) = 120.0 g

- Now, determine the percentage atom economy for the synthesis of 2-phenylpropane. Give your answer to the nearest whole number.

Answer

Atom Economy = 120/(78·0+78.5+133·5)×100 = 41%

Clearly this reaction is not particularly efficient. And if you look back at Figure 3, the atoms that get 'wasted' are in colour.

Note that when calculating atom economy you need to consider the number of atoms or molecules of reactants and products in the equation.

In Figure 3 – this isn't an issue, the equation indicates you have one molecule of each of the **reactants** and products.

But think back to the synthesis of ammonia:

$$N_2 + 3H_2 \rightarrow 2NH_3 \quad \textbf{(1)}$$

Here you have 3 molecules of hydrogen reacting with one molecule of nitrogen so in this case you would need to multiply the formula mass of hydrogen (H_2) by 3, and NH_3 by 2 in your calculation.

- Calculate the atom economy for the synthesis of ammonia according to reaction **2.1** (the relative atomic mass of nitrogen = 14.0)
- Atom economy = 34/(28 + 6) = 100%

In addition, practical considerations may also impact the efficiency of a chemical process. In chemical reactions there are other components; the reaction may take place in a solvent, or there may be additional substances added during the reaction (auxiliary chemicals). These are *not* accounted for in Atom Economy calculations but will contribute to the environmental impact of the process concerned.

4.2 The Principles of green chemistry

The 12 principles of green chemistry provide a basis with which to assess the sustainability of a chemical manufacturing process or procedure. These are illustrated in Figure 4.

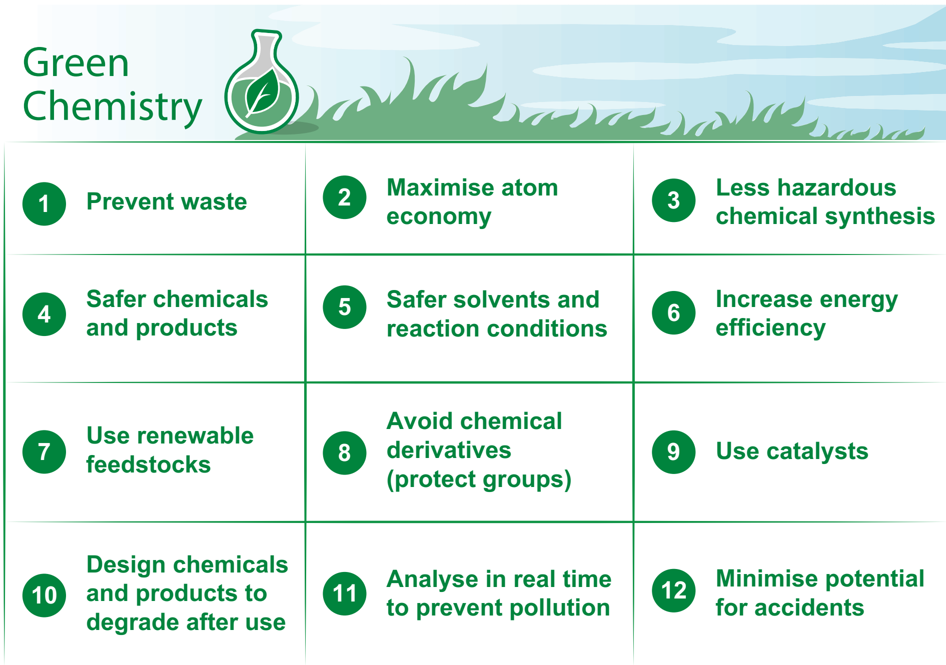


Figure 4 The 12 principles of Green Chemistry

You can find out a little more about each of the principles below.

The 12 principles of green chemistry

1. **Prevent waste**

   It is better to prevent waste than to treat or clean up waste after it is formed.

2. **Maximise atom economy**

   Synthetic methods should be designed to maximise the incorporation of all process materials into the final product.

3. **Less hazardous chemical synthesis**

Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

4. **Safer chemicals and products**

Chemical products should be designed to do what they are intended to do (their required function) while reducing toxicity.

5. **Safer solvents and reaction conditions**

The use of auxiliary substances (e.g. solvents or extraction agents) should be made unnecessary wherever possible, and harmless when used.

6. **Increase energy efficiency**

Energy requirements should be recognised for their environmental and economic impacts and should be minimised. Synthetic methods should ideally be conducted at ambient temperature and pressure.

7. **Use renewable feedstocks**

A raw material should be renewable rather than depletable, wherever technically and economically practicable.

8. **Avoid chemical derivatives (protect groups)**

Unnecessary derivatisation – chemical modifications to a molecule during a synthesis, often used to protect a **functional group** – should be avoided whenever possible.

9. **Use catalysts**

The use of selective catalytic reagents is superior to stoichiometric reagents (i.e. those that are used up in a reaction). You'll recall catalysts do not undergo a permanent change during a reaction ( ).

10. **Design chemicals and products to degrade after use**

Chemical products should be designed so that at the end of their function they do not persist in the environment but break down into innocuous degradation products.

11. **Analyse in real time to prevent pollution**

Develop analytical techniques for real-time in-process monitoring and control prior to the formation of hazardous substances.

12. **Minimise potential for accidents**

Substances and the form of a substance used in a chemical process should be chosen to minimise the potential for chemical accidents, including releases, explosions and fires.

Let's return to the 2-chloropropane synthesis and put its "green credentials" to the test. First a reminder of the reaction.

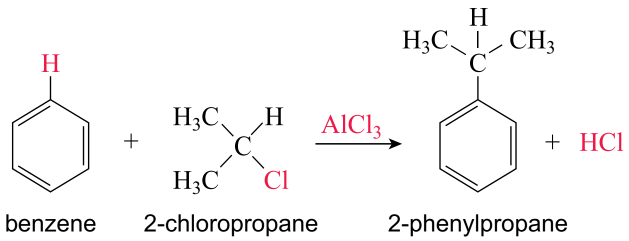


Figure 5 Synthesis of 2-phenylpropane

- Which of the principles of green chemistry are not followed?
- Based on what you know about this reaction, Principles 1 and 2 are violated as waste is produced because not all of the chemicals from the reactants are incorporated into the desired product. Principle 7 is not followed because the chemicals are non-renewable.

Less obvious, but to this you could add:

Principle 6 is violated, since a large amount of energy is required especially during removal of the excess benzene.

Principle 12 is not obeyed as benzene is highly flammable.

This is by no means a complete list, but it does give you a flavour of the types of consideration involved.

In fact there *is* a greener way of producing 2-phenylpropane which you'll look at next.

4.2.1 A greener way of making 2-phenyl propane

Industrially, 2-phenylpropane is now synthesised by the reaction of benzene with propene using a **catalyst** (Figure 4).

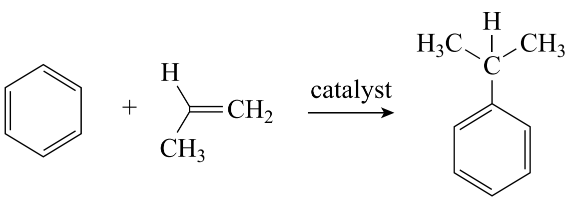


Figure 6 Alternative synthetic route to 2-phenylpropane

The **catalyst** is an aluminosilicate (an oxide based on aluminium and silicon), which does not dissolve in the reaction mixture and so can be recovered and recycled.

Also, no by-products are formed in the reaction.

- What is the atom economy of this reaction?
- 100%; all atoms of the two reactants are incorporated into in the product. As the catalyst is recycled it is not considered.

At this point you will move away from chemical manufacture to take a look at the very building blocks of chemical compounds themselves, the **elements**, in particular problems around their availability and how can we use them in a more sustainable way.

5 Elements at Risk

There are two key factors that determine the availability of an **element** to chemists: supply and cost.

5.1 Supply

The Periodic Table is the iconic depiction of all the known chemical **elements**, organised by **atomic number**. It is one of the iconic images most of us remember from our school days, perhaps even being taught weird mnemonics to help us remember at least a fair chunk of it.

But Figure 7shows a somewhat different version of the Periodic Table. In this case the area occupied by each element represents its abundance: the greater the area, the more common the element is. Importantly it also highlights those **natural elements** that are being overused and are running out.

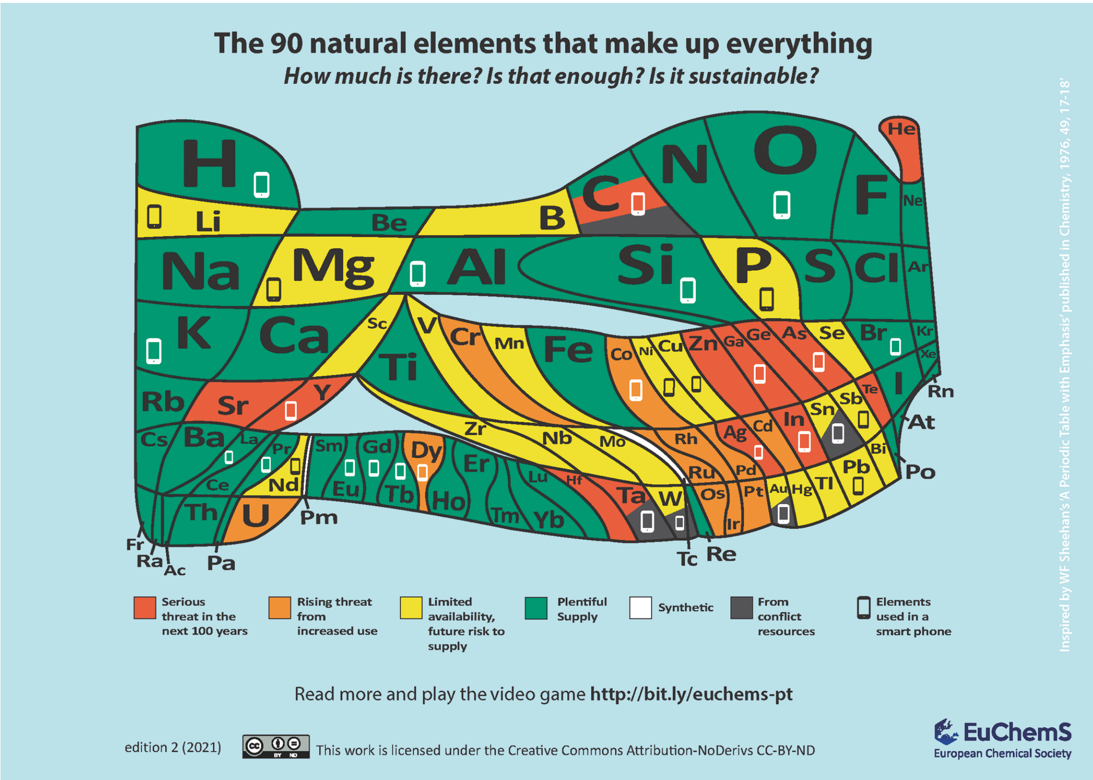


Figure 7A form of the Periodic Table showing those elements in plentiful supply and those under serious threat of running out

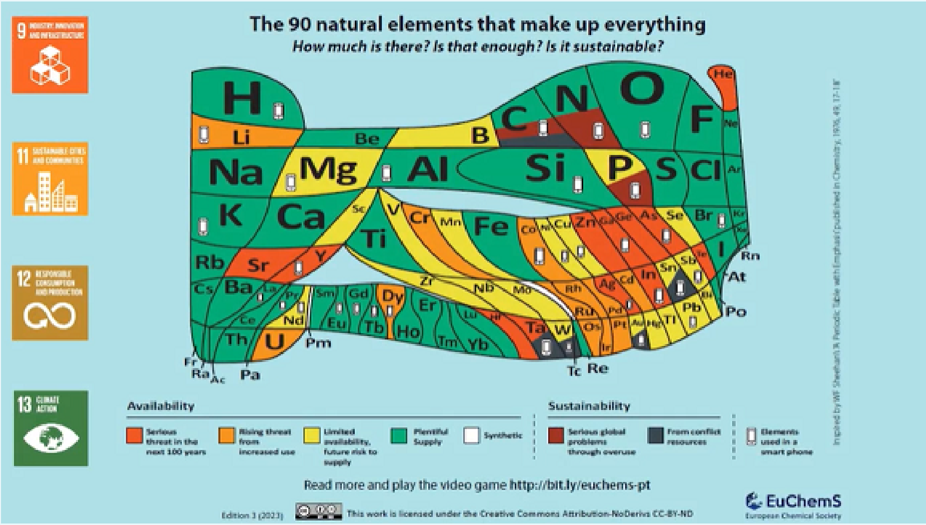
Activity 4 Sustainability and The Periodic Table

Allow about 20 minutes

You can find out more about the way the elements are represented in Figure 7 and in the two videos below, including the drive to recycle elements in low abundance.

Video content is not available in this format.

Video 5 The Periodic Table and sustainability (part 1) (video: ©The Open University)



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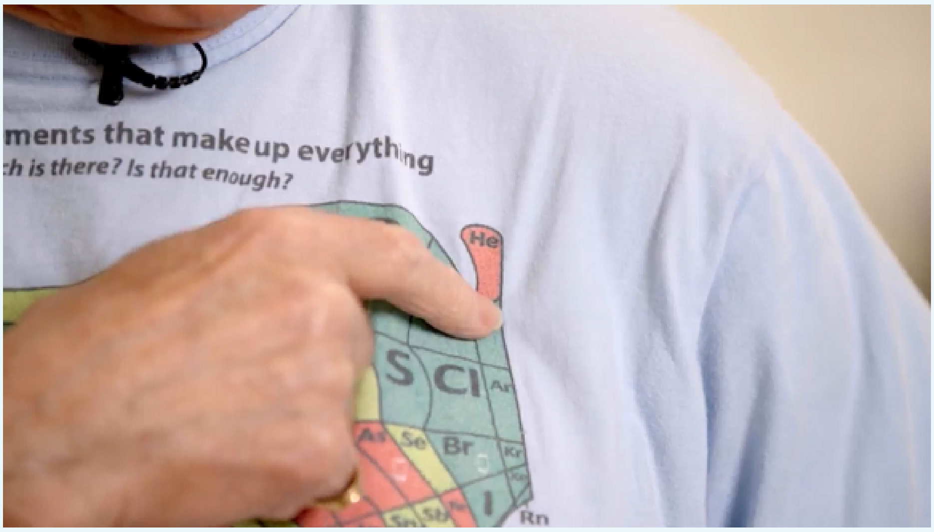
Video 6 The Periodic Table and sustainability (part 2) (video: ©The Open University)



- What role does the element indium play in mobile phones?
- The compound of indium, indium tin oxide (ITO) enables touchscreens to work – it is electrically conducting, sticks to glass and is transparent.

- What is the important clinical application of helium, which means it is essential we have a continued supply of the gas?
- Liquid helium is the coolant used in MRI scanners. As you saw in Video 6, hospitals tend to recycle helium.

- Why is the use of helium filled party balloons justifiably frowned upon, and why are they banned in Gibraltar?
- Helium is a finite resource; there are only a few places on earth where it is found. The gas readily escapes into outer space if released and lost for ever, its use in balloons would there seem incredibly wasteful. In addition, given the likelihood plastic balloons may end up in the sea, thus harming marine life, the Gibraltar government has banned their use.

So you have seen that many ‘at-risk’ elements are found in consumer electronics, such as mobile phones and computers.

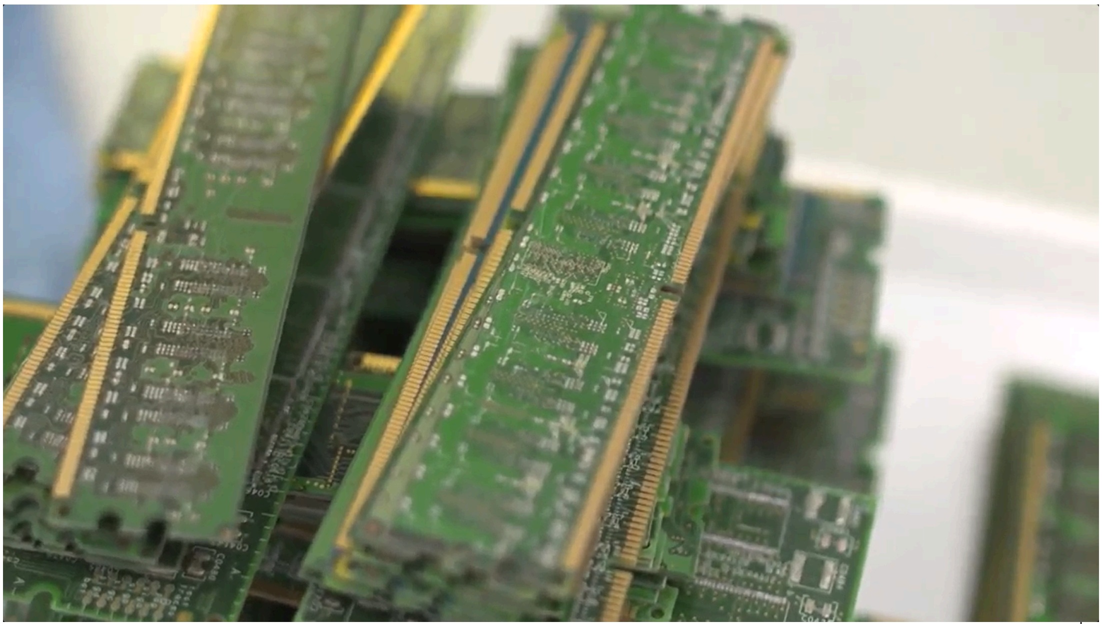
Technologies are being developed that can be utilised for the recovery of metals from electronic devices and electronic waste (e-waste) – this is part of so-called urban mining, where valuable materials are recovered from urban waste of various types .

Best known for the manufacture of UK coins, the Royal Mint based in Llantrisant, South Wales is carrying out ‘urban mining’, using innovative chemical processes to recover precious metals. Working in partnership with an international clean technology partner, it is using room-temperature chemistry to leach gold from printed electronic circuit boards. This gold is precipitated out and formed into ingots that can be used in a range of products – another example of a circular economy.

This work is described in the following video.

Video content is not available in this format.

Video 7 Extracting gold from e-waste



5.2 Cost

Concern over supply is not the only reason for recycling elements. Recycling can be cost effective too. For example, consider aluminium – the most abundant metal on Earth.

Aluminium is extracted using **electrolysis** from aluminium oxide found in the mineral bauxite. In this process you require a metal ore which has been heated to a temperature high enough to convert it into a liquid. But this is particularly problematic in the case of aluminium extraction, as aluminium oxide requires a temperature of 2000^{o}c in order to melt it. This would be incredibly energy consuming and too expensive to be economically viable.

Instead, aluminium oxide is dissolved in molten cryolite, Na_3AlF_6 , which has a much lower melting point then aluminium oxide, meaning the electrolysis reaction can be carried out at about 950^{o}C.

However, even so, aluminium extraction is still a highly energy-intensive process.

Aluminium production on Anglesey

For many years, aluminium production was carried out on the island of Anglesey in North Wales and used over 12% of the total electricity consumption of Wales. Electricity was supplied by the nearby Wylfa nuclear power station (below), the closure of which in 2010 led to production of aluminium on the island also coming to an end, as an economically viable source of electricity was not available.

Figure 8 Wylfa nuclear power station

So, even though there is plenty of aluminium ore around (look back at Figure 7), recycling aluminium (Figure 9) which involves re-melting the metal, saves almost 95% of the energy required to recover aluminium from its ore, making it a more economical source of the metal.

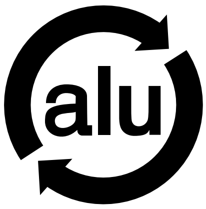


Figure 9 On-product recycling label, indicating it is made from aluminium and can be recycled

In fact the physical and chemical properties of aluminium must be thanked for this saving:

- Aluminium melts at 660^{o}C, which means the aluminium-recycling process operates at a much lower temperature than extraction by **electrolysis**.
- Aluminium is resistant to corrosion owing to the formation of a thin oxide layer on its surface, which protects the underlying metal and is another plus point in favour of recycling.

6 Summary

In this course, you looked at how the chemical industry is shedding its dirty and polluting image, as it moves towards a more sustainable approach to chemical manufacture with a reduced environmental impact.

You looked at:

- The UN Sustainable Development Goals which aim (by 2030) to end poverty, protect the planet and ensure prosperity for all.
- The circular economy which is based on reuse and recycling of materials or products in a sustainable and environmentally friendly manner.
- The Haber–Bosch process for the production of ammonia for fertilisers, and the challenges to chemists to produce the gas in a way that reduces the huge energy requirements that currently exist.
- The 12 principles of green chemistry that encourage the design of sustainable chemical processes.
- Atom economy as a metric for the efficiency of a chemical manufacturing process.
- The imperative for the recycling and reuse of many elements as demand increases, and their availability diminishes.

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OpenLearn Sustainability Hub

Acknowledgements

This free course was written by Rob Janes and was first published in August 2026.

OpenLearn editor: Dale Harry

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Images

Figure 1: Photograph of Widnes in the late 19th century showing the effects of industrial pollution https://commons.wikimedia.org/wiki/File:Widnes_Smoke.jpg

Figure 2: (adapted from: Catherine Weetman,
https://commons.wikimedia.org/wiki/File:Linear_versus_circular.jpg
https://creativecommons.org/licenses/by-sa/4.0/deed.en

Figure 4: The 12 principles of Green Chemistry: adapted from
https://www.labroots.com/tag/green-chemistry/webinarshttps://www.labroots.com

Figure 7: A form of the Periodic Table showing those elements in plentiful supply and those under serious threat of running out
https://www.euchems.eu/wp-content/uploads/2019/10/Highlights-template-4.jpg
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Figure 8: Charles Hawes/Getty Images

Figure 9: aluminium recycling label symbol

Videos

Video 1: How to solve the plastic problem: made by Gemma Green for The BBC and The Open University © BBC and The Open University

Video 2: UN SDGs: courtesy: Department of Global Communications United Nations, New York https://www.unmultimedia.org/avlibrary

Video 3: extract: The Haber–Bosch process: photographic images (drone) Suwin Puengsamrong /Alamy Stock Photo ; (Eutrophication in a river in Suffolk) geogphotos/ Alamy. ©The Open University

Video 4: Affordable and clean energy: (identified Illustrations: adapted from: C. Niether, S. Faure, A. Bordet, J. Deseure, M. Chatenet, J. Carrey, B. Chaudret and A. Rouet, Nature Energy, 2018, 3, 476; Alamy). ©The Open University

Video 5: The Periodic Table and sustainability (part 1) (identified images; photo of recyclable label: Martin Lízal/Shutterstock; The 90 natural elements that make up everything https://www.euchems.eu/wp-content/uploads/2019/10/Highlights-template-4
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Video 6: The Periodic Table and sustainability (part 2): (identified images: Alamy; MRI scanner: in Chialvo, C & Sayles, T & Diederichs, Jost & Spagna, Stefano & Gabal, Miguel & Sesé, J. & Rillo, Conrado. (2014). Smart Energy Compressors for Helium Liquefiers) ©The Open University

Video 7: Recycling Gold from Electronic Waste Recycling Gold from Electronic Waste courtesy of The Royal Mint

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Glossary

Atomic number

The number of protons in the nucleus of an atom.

Catalyst

A substance that increases the rate of a chemical reaction. The **catalyst** itself does not undergo a permanent change.

Chemical formula

A representation of the relative proportions of elements in a compound using chemical symbols.For example, the chemical formula of the nitrogen molecule is N_2, where N is the chemical symbol for nitrogen and the subscript 2 tells you how many nitrogen atoms are in the molecule.

Chemical equation

Representations of chemical reactions. A chemical equation must be balanced, so the number of atoms on the left-hand side of the equation is equal to the number of atoms on the right-hand side.

Electrolysis

A chemical reaction driven by electricity.

Electrode

The conducting points through which an electric current enters or leaves something, for example, a battery or electrolysis reaction

Element

A single substance that cannot be split into a simpler substance

Functional Group

An atom, or a group of atoms, that has similar chemical properties whenever it occurs in different compounds. Functional groups define the characteristic physical and chemical properties of families of organic compounds

Natural elements

Elements up to 94 which are found in nature (e.g. obtained from minerals). Elements with higher atomic number are synthesised in the laboratory

Organic compound

Compounds based on carbon.

Product

The compound(s) formed as a result of a chemical reaction.

Reactant

The starting materials in a chemical reaction.

Relative atomic mass

A set of numbers, one for each chemical element.The ratio between the numbers for any two elements being equal to the ratio between the average masses of their atoms. The scale of numbers is fixed by assigning a value to one particular type of atom carbon-12, $^{12}_{6}\mathrm{C}$, where the relative atomic mass of carbon is taken as exactly 12 and values for other atoms are defined relative to this.

Solution

A liquid mixture made up of a solute dissolved in a solvent. The solvent is present in the largest amount in the mixture .