A Sustainable Global Society

How Can Materials Chemistry Help?

A white paper from the Chemical Sciences and Society Summit (CS3) 2010
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ABOUT THE CHEMICAL SCIENCES AND SOCIETY SUMMIT (CS3)

The annual Chemical Sciences and Society Summit (CS3) brings together the best minds in chemical research from around the world and challenges them to propose innovative solutions for society's most pressing needs in the areas of health, food, energy, and the environment. This unique event boasts an innovative format, aiming to set the course of international science, and rotates each year among the participating nations.

A Sustainable Global Society summarises the outcomes of the second annual CS3, which focused this time on Sustainable Materials. Thirty top materials chemists from the five participating countries assembled in London to identify the scientific research required to address key global challenges, and to provide recommendations to policy makers. This report presents an international view on how materials chemistry can contribute positively to creating a sustainable world.

The CS3 initiative is a collaboration between the Chinese Chemical Society (CCS), the German Chemical Society (GDCh), the Chemical Society of Japan (CSJ), the Royal Society of Chemistry (RSC) and the American Chemical Society (ACS). The symposia are supported by the National Science Foundation of China (NSFC), the German Research Foundation (DFG), the Japan Society for the Promotion of Science (JSPS), the UK Engineering and Physical Sciences Research Council (EPSRC), and the USA National Science Foundation (NSF).

This White Paper was compiled and written by Carol Stanier and James Hutchinson.

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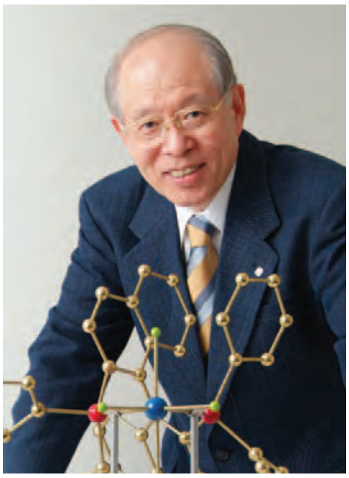

FOREWORD

Since the most ancient of times, humanity has depended on the blessings of the sun and the abundant mineral and living resources of nature. These resources, however, have always been unevenly distributed and of varying importance depending on the times. For this reason, peoples and nations have clashed repeatedly in their eagerness to claim them as their own.

Over the centuries, science and technology, the products of human ingenuity and our quest for understanding nature, have enabled us to make effective use of natural resources for the building of rich civilisations. Superior science-based technologies have protected fragile humanity from the dangers of nature, provided safety and security, and made possible convenient and comfortable lifestyles. In the 20th century, science-based technologies effectively extended the average lifespan within the developed nations from 45 to 80 years, and provided diverse external devices that have significantly enhanced humanity's inherent intellectual and physical abilities.

On the other hand, we have only achieved limited success in making effective use of our limited resources. Humanity's drive for an increasingly enhanced level of advanced civilisation has, ironically, led to an alarming depletion of essential resources. And there appears to be no end to global conflicts over access to these resources.

The ideal for the 21st century is a civilised global society that respects cultural diversity. When diverse ethnic groups are allowed to make use of the natural resources in the regions where they live, it should be possible for them to maintain the unique culture they have inherited from their ancestors and to build a rich, civilised society that does not impinge on the rights of others. The world needs science and technologies that are firmly grounded in this premise.

Ever since the Industrial Revolution, humanity's insatiable appetite for energy has caused us to release large volumes of harmful carbon dioxide into the Earth's atmosphere, and this is adversely affecting the entire world. We need to make a major paradigm shift from one that is based on consuming finite fossil reserves to one that is based on replacing resources as we consume them in a manner similar to, but more efficient than, natural photosynthesis. How wonderful it would be if we could easily transform sunlight into electrical energy and freely create useful materials from abundant elements. Innovative science and technology focused on securing the continuous supply and replacement of resources is what is needed to achieve a truly sustainable society.

International cooperation is clearly essential to achieving this goal, however the problems of resources and the environment are complicated by political and economic concerns. It is heartening, therefore, to know that chemists engaged in materials science representing China, Germany, Japan, the United Kingdom and the United States have gathered together in London to engage in intellectual discourse and to offer policy recommendations on the subject of sustainable materials.

Chemistry is the science of materials and substances, and the transformations they undergo. As such, chemistry is a central science, broadly spanning many disciplines. Chemistry provides the wisdom we need to achieve sustainability, to solve, in other words, the issues that threaten humanity's continued existence. The chemist has a mandate to counsel society on the possible solutions that can be achieved through chemistry. It is to be hoped that the recommendations of the CS3 2010: Sustainable Materials summit will be widely disseminated among governments and societies throughout the world as we strive together to achieve the ideal, and sustainable, international community.

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EXECUTIVE SUMMARY

With the aid of materials chemistry we can create a world in which energy use need not be limited, where we can decrease carbon dioxide (CO_2) emissions, reduce our dependency on fossil fuels and minimise the impact we are having on our environment. We can prevent further depletion of our scarce natural resources, and create new consumer products that can enable new low-carbon and resource-efficient industries to flourish, driving economic growth.

The world's population continues to increase and is expected to have increased by 1.7 billion to over eight billion by 2030, with the majority of people living in cities. Cities place huge pressures on the supply of energy and resources, and create emissions at a rate that is unsustainable.[1]

Living standards are improving in many parts of the world.[2] If everyone today had living standards equivalent to those prevalent in North America, between two and three times the Earth's natural resources would be needed.[3]

The coupled effects of population growth and improved standards of living put great strain on the planet and on our remaining accessible resources. We are rapidly approaching the maximum rate at which we can extract oil from the planet. Our appetite for energy is producing increasing quantities of CO_2, a pollutant that contributes to the warming of the planet and which currently cannot be removed or stored in any efficient way. Supplies of other natural resources are also a concern. Current assessments suggest that we will soon need to identify alternative sources of a number of strategic minerals.

We are damaging our planet in an irreparable and sometimes unquantifiable fashion. It is clear that our current use of natural resources is not sustainable. Although chemistry has sometimes been rightly or wrongly blamed for damaging the environment, it has also provided many of the material benefits without which we could not survive today such as pharmaceuticals, plastics and fuels.

A Sustainable Global Society outlines five key areas in which materials chemists, through collaboration with other scientists, industry and policy makers, can seize exciting opportunities to address global challenges. Materials chemistry will underpin many of the required solutions to some of the most important energy and environmental problems in today's society:

- A growing population and increasing living standards are increasing world demand for energy. This demand may soon outstrip the amount of usable energy that can be obtained using currently-available methods. Materials chemists will help to develop new, sustainable energy conversion and storage technologies that can meet future energy demands, and without increasing harmful emissions of CO_2.
- It is projected that the Earth will likely warm by between 2 and 4.5 °C in the next 100 years, largely as a result of human-made CO_2 emissions. Materials chemists can help to reduce CO_2 emissions by improving carbon capture and storage (CCS) systems and developing novel ways of activating and using CO_2 as a value product for fuels and chemical feedstocks rather than waste.

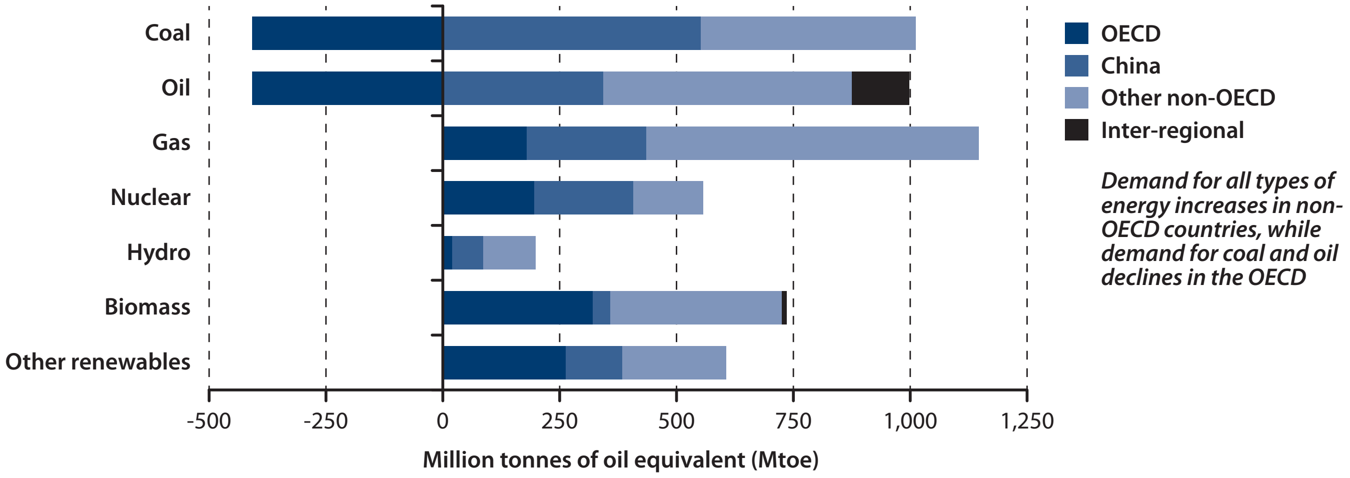


Figure 1: Incremental primary energy demand by fuel and region 2008-2035[4]

- Approximately 90% of oil extracted from the Earth is used to produce fuel; the remainder is used to make everything from convenience plastics to life-saving pharmaceuticals. Materials chemists can help to reduce our dependency on fossil fuels and feedstocks by developing methods to efficiently obtain petroleum from low-quality sources, and processes to efficiently and sustainably utilise fossil fuel alternatives.
- Supplies of scarce natural resources are dwindling at an alarming rate and shortages will hit within a generation. Materials chemistry can help to reduce, replace and recycle the use of scarce natural resources in many applications, as well as developing alternative new materials based on earth-abundant elements.
- The pressures created by a growing world population are damaging the environment. Materials chemists can use the principles of green chemistry to meet our energy, material, and water needs in ways that are non-harmful and sustainable. New technologies can be developed to better monitor and remove air, soil and water pollutants from the environment.

Fundamental advances in science underpin many of these proposals – support for curiosity-driven (blue-skies) research must be in place to maintain the flow of future scientific breakthroughs.[5] *Chemistry for Tomorrow's World: a roadmap for the chemical sciences*, provides recommendations to create and maintain a supportive framework to address global challenges.[6] A sustainable and long-term strategy for investment in science will be vital to the continued well-being, comfort and wealth of modern society.[7,8]

With the aid of materials chemistry, we can create a world in which our energy requirements are delivered sustainably, where usable energy can be produced, stored and then supplied wherever it is needed. We can minimise and remove pollutants from our environment as we create new consumer products which place less of a burden upon our natural resources. While the challenges in each geographical and political arena may vary, it is important that national thinking not be limited to the challenges of that country alone.

Many of these goals should be achievable within a relatively short timescale, and will help to improve the world for this generation and the succeeding ones. Although financial investment is required, in the mid-to-longer term this investment can be economically beneficial,[9] will create new, greener industries that create sustainable jobs, and will ensure global security. We must act now if we are to reap the benefits materials chemistry can offer.

1. ENERGY CONVERSION AND STORAGE

A growing population and rising living standards are increasing world demand for energy. This demand may soon outstrip the amount of usable energy that can be obtained using currently-available methods. Materials chemists will help to develop new, sustainable energy conversion and storage technologies that can meet future energy demands without increasing harmful emissions of carbon dioxide (CO_2). Sustainable solar energy technologies can be developed that efficiently harvest energy from sunlight anywhere on the planet. Innovative new fuel cells can efficiently exploit renewable sources of energy. Next-generation battery and chemical energy storage technologies will enable us to flexibly store and transport energy, and to fully utilise intermittent forms of energy.

The Challenge

By the year 2030 the world's growing population and rising living standards may lead to a 50% increase in the global demand for energy,[4] and such a demand may exceed the available conventional supply.[10]

Measures to meet an increasing demand for energy must not result in a corresponding increase in CO_2 emissions, a greenhouse gas that contributes to climate change. The majority of electricity generated worldwide is currently produced in fossil-fuel-powered power stations. Although these power stations are reliable, they produce significant amounts of CO_2. In developed countries alone, electricity generation accounts for approximately 30% of CO_2 emissions. It should be possible to reduce CO_2 emissions from fossil fuel power stations (see Chapter Two: CO_2 Capture, Activation and Use). However, by some estimates we may still require more energy in 2030 than may be feasibly obtained from fossil sources.[11]

New technologies must not leave future generations with an unwanted legacy of additional problems.

We require improved methods of generating usable energy from sustainable, non-polluting sources, then storing this energy in a form where it can be easily transported or used. The energy from sunlight can be converted into electricity using solar panels, for instance, then stored by an energy carrier such as a battery.

Materials chemists, working with other scientists and engineers, are developing new forms of energy conversion and storage technologies that should have the flexibility to meet the energy needs of both consumers and industrial users,[12] while producing fewer emissions than current systems.

Energy conversion

The conversion of energy from one form to another frequently involves a chemical reaction. Detailed mechanistic understanding of these chemical reactions is vital to developing new materials and processes that can be used to drive them in affordable and sustainable ways.[5]

Solar energy

Sunlight is abundant everywhere on Earth and is the energy source of choice for the future. Solar energy can be captured and converted to useful forms via photovoltaic (PV), photoelectrochemical, photocatalytic, or thermoelectric technologies. To have a significant impact, these technologies must be able to harness solar energy on a large scale.[13]

Materials chemists can develop new, more efficient and durable PV cells made from cheap, abundant and easily-processed materials. Photovoltaics generate electrical power by converting solar radiation into electricity. PV technologies are already widespread, and it is generally agreed that they will play a major role in harnessing solar energy for future energy solutions.[14] However, there are disadvantages with currently-available photovoltaics. Many current PV technologies are based on silicon, an abundant element that must be of very high purity for solar power applications, making current silicon-based technologies very expensive.

Inexpensively manufactured PV cells with greater efficiencies are required[13] – current-generation carbon-based ('plastic') cells, that are much more amenable to inexpensive fabrication processes, can convert roughly 8% of the solar power that falls on them; typical silicon-based solar cells can convert up to approximately 20%. With research and investment, new technologies could place photovoltaics at the centre of future global energy strategies.[7]

Photoelectrochemical cells convert solar energy into chemical fuel by using the energy from sunlight to drive chemical conversions of readily-available substances such as water and CO_2 to produce useful chemicals or fuels. Photocatalysis is the rate acceleration of such a reaction by a catalyst. These processes are often collectively termed 'artificial photosynthesis' because they mimic the way in which plants generate chemical energy from sunlight.

Artificial photosynthesis technologies are not currently affordable or sustainable for widespread use. New, commercially-viable photocatalyst technologies based on affordable, abundant materials are needed.[13] The process of discovering and optimising new materials with desirable physical properties for solar energy conversion to electricity and fuels will require new systems for efficiently synthesising, screening and optimising large numbers of new chemical compounds.

Thermoelectric materials, which generate electricity directly from heat, can also be used for energy conversion applications. Approximately 90% of the world's electricity is generated by heat energy, typically operating at 30–40% efficiency.[15] Thermoelectric devices could convert some of the waste heat from these processes into useful electricity. New thermoelectric generators are required that can utilise heat energy from the sun, and waste heat from other energy conversion processes, in an efficient and cost-effective manner.

How will materials chemistry help?

- Materials chemists will develop new solar cells with greater efficiencies at lower cost. This will require materials chemists to synthesise a diverse range of cost-effective, new materials that absorb the entire solar spectrum and produce a high density of mobile, long-lived charge carriers (particles that carry electric currents).
- Materials chemists will design and prepare alternative, inexpensive materials that can efficiently mimic photosynthesis, with far higher efficiency than that of plants (~2%).
- Materials chemists will explore and optimise new thermoelectric materials made from abundant elements that can convert solar energy, and waste heat, into electricity.

Fuel cells and biological energy conversion systems

A fuel cell is an electrochemical cell that converts the oxygen in air and a fuel, such as hydrogen, methanol or a hydrocarbon (e.g. from biomass), into electricity. Fuel cells are different from conventional electrochemical cell batteries in that they consume fuel from an external source, which must be replenished.

To become commercially feasible, more efficient and low-cost fuel cells are required, containing components that are made from sustainable materials. Proton exchange membrane fuel cells, also known as polymer electrolyte membrane (PEM) fuel cells, are being developed for transport applications as well as for stationary fuel cell applications and portable fuel cell applications. The development of new materials with higher catalytic activity than the standard carbon-supported platinum particle catalysts (currently-used in PEM fuel cells) is required.

A solid oxide fuel cell (SOFC) has a solid oxide or ceramic, electrolyte. Although currently-available SOFCs run at very high temperatures, advantages of this class of fuel cells include high efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost. New, low-cost catalysts and electrolyte materials (based on earth-abundant elements), for SOFCs that can run at lower temperature and with higher power densities, could improve currently-available technologies.

Biological energy conversion systems are potential, sustainable alternatives to conventional energy supplies. Microbial fuel cells (MFCs) convert chemical energy from a suitable substrate into electricity using bacteria and, as such, could supplement traditional fuel-cell technologies in the future. With development, MFC systems could be used to generate energy from organic matter in waste water and in low-grade waste.

How will materials chemistry help?

- Materials chemists will design new polymer electrolytes and high-temperature proton conductors, which contain mobile hydrogen ions, as charge carriers for fuel cells.
- Materials chemists will construct new mixed ion-electron conductors for solid oxide fuel cells by discovering and optimising new catalysts with high stability and activity, made from earth-abundant elements.
- Materials scientists, biotechnologists, and engineers will collaborate to develop MFC technologies through fundamental multidisciplinary research.

Energy storage

There is a pressing need for robust, scalable energy storage technologies. Many renewable energy sources, for example solar and wind, are intermittent, generated remotely and therefore difficult to feed directly into an electrical grid. However, if energy can be efficiently and safely stored, then a continuous supply is not required. Very large-scale storage systems will enable the energy produced from intermittent sources to be stored for later use.

Batteries and thermal energy storage

The energy density of current battery technologies must be improved in the short-term.[†] Advanced lithium-ion batteries will be a transitional energy storage solution. Demand for lithium may soon exceed the available global supply, and new-generation batteries based on other accessible, more abundant elements will be required (see Chapter Four: Conservation of Scarce Natural Resources).

New batteries and thermal energy storage devices based on abundant, sustainable materials are required. Solid-state batteries, that use a solid material rather than a liquid to conduct electricity, are already available and may be feasible, as will a range of other technologies. Thermal energy storage devices that store heat energy in reservoirs (such as molten salts, phase change materials, and even chemical reactions) for later use, can be developed for storing energy from intermittent sources. A flow battery is a form of rechargeable battery in which the electrolytes flow through the electrochemical cell. Additional electrolyte is stored externally, generally in tanks, and is usually pumped through the cells of the reactor. Flow batteries can be rapidly 'recharged' by replacing the electrolyte liquid and hold great potential for large-scale applications. New materials are required to develop improved flow batteries with higher energy densities.

How will materials chemistry help?

- Materials chemists will provide new materials for high-energy-density components to improve battery performance.
- Materials chemists will help to develop an array of new energy storage technologies as durable and safe alternatives to conventional batteries, including new-generation solid state and flow batteries and thermal energy storage devices.

Chemical energy storage and hydrogen

The chemical bonds in fuel molecules are an effective means of storing energy because they release energy when reacted with oxygen. Combustion (or burning) is a means by which this energy can be released. Chemical energy storage devices can be coupled with an appropriate means of energy conversion (see above) to produce fuels, such as hydrogen or hydrocarbons, that can be burned when and where required.

Hydrogen is a highly-sustainable form of chemical energy because the only product released from its combustion is water. It can be burned directly or reacted with CO_2 (or molecules derived from biomass) to produce liquid hydrocarbon fuels (see Chapter Two: CO_2 Capture, Activation and Use).

Hydrogen is usually obtained from fossil sources (such as methane in natural gas). However, these sources are unsustainable and more energy is currently required to produce hydrogen than would be obtained from burning it. New methods of producing hydrogen using a renewable energy source would enable hydrogen-based technologies to develop into more efficient and cost-effective forms of chemical energy storage.

[†] *In energy storage applications the energy density relates the mass of energy stored to the volume of the storage equipment. The higher the energy density, the more energy may be stored or transported for the same amount of volume.*

The electrolysis of water is a means of splitting water into hydrogen and oxygen, and is a promising method of producing hydrogen. Using an energy source such as sunlight to provide the electricity to drive the reaction, water electrolysis can produce a sustainable supply of hydrogen that does not require fossil fuels as feedstocks. With improved efficiency of photovoltaics, electrolysis, and gas separation technologies, water electrolysis could become an effective means of producing hydrogen to store energy, to make fertiliser, and to form liquid hydrocarbon fuels.

Artificial photosynthesis applications are also promising. These could produce natural gas (methane) or alcohols as fuels from sunlight, CO_2, and water. The use of CO_2 in chemical energy storage systems is discussed in Chapter Two: CO_2 Capture, Activation and Use.

How will materials chemistry help?

- Materials chemists will design new catalytic systems to produce hydrogen from water electrolysis, coupled with improved gas separation technologies to harvest the hydrogen produced.
- Materials chemists will design and develop new photocatalytic materials that can directly produce hydrogen from water without an electrolyser.
- Materials chemists will help to develop innovative new forms of chemical energy storage, including means of producing fuels from sunlight, CO_2, and water (see Chapter Two: CO_2 Capture, Activation and Use).

Large- and small-scale energy systems

Energy systems must consist of an appropriate means of converting energy, such as solar panels, coupled with a robust and sustainable means of energy storage (see above) and efficient transmission from the place of production to the place of use. Both large- and small-scale energy systems have great room for improvement.[16] Current solar cell materials coupled with existing battery technology, for instance, would be acceptable for use in energy systems in the short term.

Low-loss energy transmission systems will be required to accommodate the mismatch between the location of energy generation and the location of use. Current high voltage grids are inefficient – significant amounts of energy are lost by transporting electricity over long distances using an alternating current and conventional conducting materials such as copper. High voltage direct current (HVDC) grid technologies could provide energy for Europe from solar power stations in the Sahara Desert, for instance.[17] Before these systems become commercially and energetically viable, the development of low-loss energy transmission lines fashioned from new superconducting materials, that can conduct electricity with minimal resistance at room temperature, will be required (currently available superconductors work at very low temperatures).

Today's electrical grids have little capacity to store energy. Large-scale energy storage systems will therefore be required if we are to increase the proportion of renewable, intermittent forms of energy conversion (such as wind, wave and solar) in our energy mix. 'Smart grids' coupled with energy storage devices (see Figure 2) could offer significant improvements in performance over existing electrical grids. The Hydrogen Office project in Scotland, for instance, has been set up to support the accelerated development of the renewable, hydrogen, fuel cell and energy storage industries.[18] Investment in the development of new and improved energy storage technologies will enable the widespread introduction of next-generation large-scale energy systems.

Smaller energy systems can be portable and useful in remote locations where it is difficult to maintain an electrical grid. These systems can give individuals or small businesses independence from a grid. Such independence has great advantages in terms of location, mobility, and security. Much of the knowledge and technology already exists to provide short-term solutions in this area. In the long term, new technologies could consist of inexpensive polymer-based solar cells (with conversion efficiencies in excess of 10%) for example, coupled with high-performance batteries. In this way, energy from the sun may be converted to electrical current by the solar cell and then stored in the battery. If such energy systems were incorporated into a fleet of vehicles, for instance, these vehicles could not only provide energy for transport, but could also function as a mobile electrical grid to provide energy for domestic use.

How will materials chemistry help?

- Materials chemists will design and develop new materials with greater efficiency, reliability and durability to deliver new energy systems, including next-generation solar cells and energy storage systems.
- Materials chemists will design and develop new materials for energy systems that are environmentally benign and not reliant on elements which are in increasingly short supply (see Chapter Four: Conservation of Scarce Natural Resources).

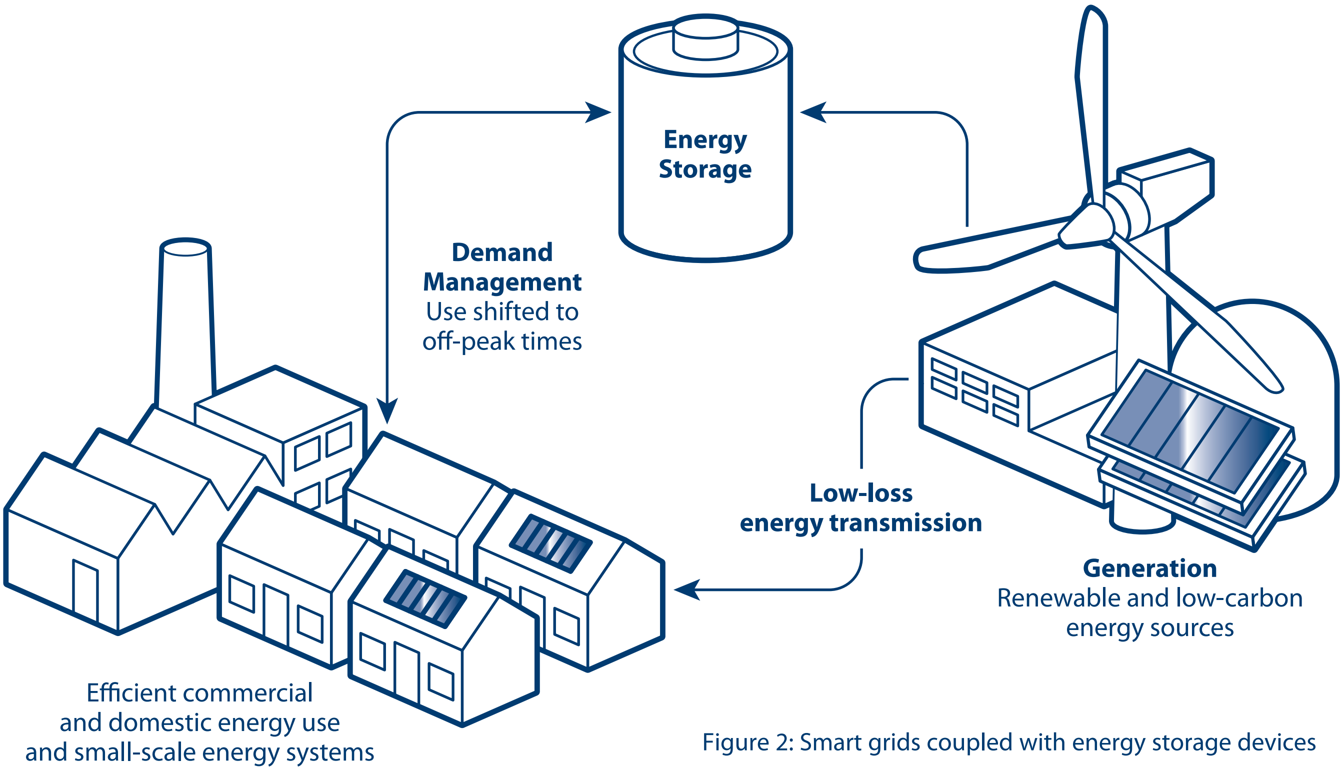


Figure 2: Smart grids coupled with energy storage devices could offer significant improvements in performance over existing electrical grids

2. CO_2 CAPTURE, ACTIVATION AND USE

It is estimated that the Earth will likely warm by between 2 and 4.5 °C in the next 100 years, largely as a result of human-made carbon dioxide (CO_2) emissions. Although carbon capture and storage (CCS) systems may help to reduce CO_2 emissions, CO_2 cannot be commercially captured at present. Materials chemists can help to improve CCS systems and to develop novel ways of treating CO_2 as a value product rather than waste. Sustainable methods can be developed to convert CO_2 into chemical products for fuel and feedstocks. Technologies to synthesise new polymers from CO_2 could be available within a few years, reducing our reliance on petrochemical feedstocks. Supercritical CO_2 can be used as a solvent in many industrial processes, as a sustainable alternative to those derived from fossil fuels.

The Challenge

CO_2 is used by plants to produce sugars and is essential for their life functions. However, CO_2 is also a growing constituent of the Earth's atmosphere. A 'greenhouse gas', its presence in the atmosphere contributes to climate change. The Intergovernmental Panel on Climate Change (IPCC)[19] estimates that the Earth will likely warm by between 2 and 4.5 °C in the next 100 years, largely as a result of CO_2 emissions from human activity.

Estimates suggest that capture of CO_2 using carbon capture and storage (CCS) technologies may be able to reduce emissions from coal power plants by 80–90%.[20] Materials chemists will help to develop reliable technologies for capture, separation and storage of CO_2. However, capture alone is insufficient to meet global emissions targets.

Materials chemistry can also provide alternatives to geological carbon storage. We can reduce CO_2 emissions by developing alternative, carbon-neutral ways to generate power (see Chapter One: Energy Conversion and Storage) and by using CO_2 to make fuels or as a value product in the chemical supply chain rather than waste. This would reduce our dependency on fossil fuels (see Chapter Three: Fossil Fuel and Feedstock Replacement Materials) and may avoid potential long-term problems associated with capture such as CO_2 leakage.[21]

Supercritical CO_2 is a form of fluid carbon dioxide that is already used industrially as a solvent and in purification processes. The widespread use of supercritical CO_2 as a processing fluid could reduce the need for traditional fossil-fuel-derived solvents for chemical processes, the disposal of which often has a negative impact on the environment (see Chapter Five: Green Materials and Processes).

The use of CO_2 to make fuels, and as a feedstock and processing fluid alone will not be enough to mitigate climate change, as the volumes of CO_2 that can be realistically sequestered in this way are quite small. However, the materials chemistry solutions described below can form part of a wider strategy to lower global CO_2 emissions. The development of industries relying on the technologies described would provide countless jobs, independent of local natural resources.

CO_2 capture, separation, and storage

Governments around the world are now committed to the establishment of commercial-scale demonstration projects for CCS[22] from gas- and coal-fired power stations.[19,20,23] Multidisciplinary materials and engineering research will be required to develop reliable CCS systems.

CCS systems will require new energy- and cost-effective materials, processes and technologies for both capture and separation of CO_2. Current carbon capture techniques currently use impractical amounts of energy and materials, and removal of impurities from captured CO_2 can render CCS systems prohibitively expensive. Novel solutions for removing impurities from CO_2 will be required that utilise robust, impurity-tolerant materials and membranes based on abundant elements. Next-generation CCS applications must function both in concentrated, stationary sources and in dilute, mobile sources.

It is recognised that CO_2 stored underground today may be mined as a value product tomorrow.[24] Such a strategy would be a temporary or transitional solution – the stored CO_2 could be utilised at a later date when suitable conversion technologies become available and conventional carbon sources become more scarce.

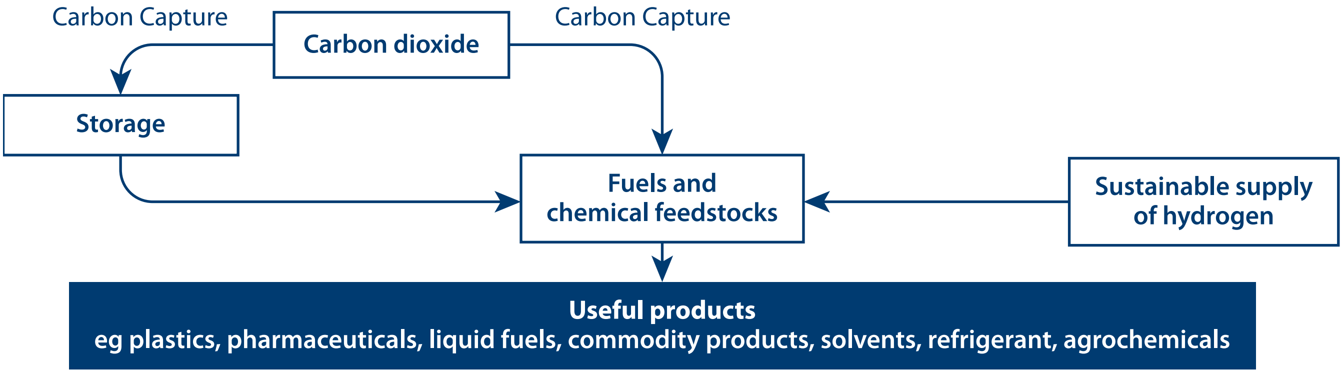


Figure 3: CO_2 capture, activation and use

How will materials chemistry help?

- Materials chemists will investigate and develop a range of CO_2 capture and purification technologies.
- Materials chemists will help to develop commercially-viable methods of storing CO_2 for future use, such as synthetic fossilisation and carbonation of mineral rocks.

CO_2 for fuels and chemical feedstocks

Although normally unreactive, it is possible to facilitate the reaction of CO_2 with other chemicals, in the presence of a catalyst, to form chemical energy-storage systems or useful new materials.[25]

Many of the day-to-day products we use are carbon-based or contain carbon sourced from petroleum. Currently around 5–10% of all petroleum produced is utilised for the production of chemicals such as plastics, pharmaceuticals and other consumer products. Demand for petrochemical feedstocks is set to rise as populations increase and technologies advance. By applying knowledge gained from fundamental research in materials chemistry and catalysis (see Chapter Five: Green Materials and Processes), it may be possible to use CO_2 as a raw material (feedstock) and feed it into the chemical supply chain.[24]

The commercial use of CO_2 as both a fuel and a feedstock will require many of the same developments. Many of the described technologies and industries are in their infancy and the projection of realistic timescales is difficult without further fundamental research.

Production of methanol

CO_2 and hydrogen gas can be combined to form methanol, a liquid fuel that can be easily transported. Methanol can then be converted by known zeolite catalysts to gasoline. Commercialisation of methanol production technologies can be achieved using catalysts based on abundant elements (see Chapter Four: Conservation of Scarce Natural Resources) and a non-fossil, sustainable supply of hydrogen (see Chapter One: Energy Conversion and Storage).

It may be possible to develop a system whereby a low-carbon energy source, such as solar energy, could be used both to extract CO_2 from the atmosphere and to provide the energy needed to drive the subsequent reaction with hydrogen (or other hydrogen sources) to form methanol.[26]

The conversion of CO_2 into methanoic acid, methanal, methanol and higher alcohols by reaction with hydrogen (or other hydrogen sources) could provide feedstocks for the production of many commodity products currently in use on a large scale. Such processes could also be feasibly introduced within a few years by modifying existing industrial plants.

Production of methane

The efficient conversion of CO_2 and water to methane gas is a potential energy storage solution. Methane is more energy-rich than methanol and therefore more suitable for combustion. Current technologies for burning methane already exist and are widespread (methane is the largest constituent of natural gas). Conversion of CO_2 to methane could reduce reliance on natural gas sources and aid the transition to low-emission, cleaner fuels in the medium term.

Production of syngas

Syngas (or synthesis gas) is a mixture of carbon monoxide (CO) and hydrogen that can be used directly as a fuel or to feed into chemical processes (e.g. the Fischer-Tropsch process) to produce hydrocarbons (for use as fuels or chemical intermediates). Syngas is a highly-important feedstock in the chemical industry and such processes are widely used on an industrial scale (see Chapter Three: Fossil Fuel and Feedstock Replacement Materials, for the use of syngas as a feedstock).

Syngas is conventionally produced from a variety of different sources including natural gas, coal, biomass and biological waste. This flexibility delivers the advantage of making it possible to adapt multiple industrial plants to produce syngas with minimal design alteration. Current syngas plants are usually very large and expensive, whereas smaller, more dispersed plants ('flexiplants') may be more beneficial.

Catalytic processes are now available to convert CO_2 into syngas using a supply of hydrogen. The widespread conversion of CO_2 into syngas using hydrogen or other hydrogen-containing materials, could be viable in the near term through the design of suitable working plants.

How will materials chemistry help?

- Materials chemists will develop catalytic processes to efficiently obtain hydrogen gas from non-fossil sources (see Chapter One: Energy Conversion and Storage).
- Materials chemists will explore new catalysts to efficiently convert CO_2 and hydrogen (or other hydrogen sources) to methanol, and CO_2 and water to methane and oxygen.
- Materials chemists can help to adapt industrial plants to produce syngas for use as a fuel and feedstock.

CO_2 as a feedstock for plastics and complex chemical structures

The technology required to convert CO_2 into polymers is currently available on a small scale and could be increased in scope and scale within a few years. Facilities already exist to incorporate gaseous building blocks into polymeric materials which could be adapted to utilise CO_2.

Methods to form complex chemical structures from CO_2, and other one-carbon building blocks, should be commercially feasible in the longer term. Development of these technologies may require 10 years or more – yet as a strategy for the sustainable production of chemical products, the use of CO_2 as a building block should remain an ultimate goal.

How will materials chemistry help?

- Materials chemists will help develop and optimise highly active, selective, sustainable and robust catalysts for chemical reactions of CO_2.
- Materials chemists will design and optimise electrocatalytic and/or photocatalytic methods to incorporate CO_2 into the supply chain (see Chapter One: Energy Conversion and Storage).

CO_2 as processing fluid and solvent

Supercritical CO_2 is a form of fluid carbon dioxide that is already used industrially in many processes, for example in the removal of caffeine from coffee beans, and as a refrigerant.[27] It has the favourable properties of low toxicity, low reactivity, and can be used at near-ambient temperatures. The widespread use of supercritical CO_2 for the purification of synthetic and naturally-occurring chemicals should be possible in the short term. This would replace the use of more toxic, complex and expensive solvents. The design of new processes will require collaboration between materials chemists and engineers.

How will materials chemistry help?

- Materials chemists will develop and optimise methods for using supercritical CO_2 as a solvent for known or new chemical reactions, as a refrigerant and in materials processing.

3. FOSSIL FUEL AND FEEDSTOCK REPLACEMENT MATERIALS

Approximately 90% of oil extracted from the Earth is used to produce petroleum. Oil is an integral ingredient to make everything from convenience plastics to life-saving pharmaceuticals, and the demand for petroleum is set to rise. Materials chemists can help to reduce our dependency on fossil fuels and feedstocks in a number of ways. Methods to efficiently extract petroleum from low-quality sources can be developed. Improved catalytic and separation processes can be designed and optimised that enable us to efficiently and sustainably utilise syngas, methane, biological feedstocks and even carbon dioxide as fossil fuel alternatives. Polymers made from new and unique biomass feedstocks may eventually overtake petrochemical-derived plastics in terms of superior properties and functionality.

The Challenge

Our modern society depends on carbon-based fuels for generating electricity, heat and propulsion and as chemical feedstocks to produce materials and commodities. Burning fossil fuels for their energy produces CO_2 that contributes towards climate change, and we may be approaching the maximum rate at which we can feasibly extract oil from the planet. We should seek to reduce our dependency on fossil fuels for generating useable energy (see Chapter One: Energy Conversion and Storage) and diversify the feedstocks we use to produce materials and commodities such as pharmaceuticals, agrochemicals and polymers.

New strategies to mediate the transition away from fossil fuels will be required. These must ensure that the wealth, security and living standards of an increasing world population do not suffer.[7]

New carbon sources should be renewable and not increase CO_2 emissions. Sustainable methods to extract petrochemicals from low-quality feedstocks, however, must be a short-term priority. Syngas and methane hold significant potential as alternatives to petroleum and coal in the short- to medium-term. The utilisation of biomass as a feedstock is a longer-term goal that could deliver processes to exploit the molecular complexity of nature for new and improved materials and polymers.

Complete independence from petroleum as a feedstock for polymers and other chemicals should be the ultimate objective. The use of CO_2 as a feedstock has the longest development time but would be a highly sustainable solution (see Chapter Two: CO_2 Capture, Activation and Use).

Processing low quality hydrocarbon feedstocks

Technologies to utilise the low- and high-sulfur feedstocks in low-quality crude oils are needed. Materials chemistry can enable clean, efficient and secure production of fuels and chemicals from low-quality fossil sources. Fundamental advances may be achievable in 10 years through focused collaboration between chemists, engineers and other physical scientists.

How will materials chemistry help?

- Materials chemists will conceive of and develop new catalytic processes to mitigate the environmental impact of low-quality hydrocarbon use.
- Materials chemists, working with engineers, will design and optimise improved engineering and reactor materials.
- Materials chemists will design and develop new chemical separation technologies to purify low-quality fossil fuel feedstocks.

Syngas as a feedstock

With the appropriate technological developments, syngas could be a sustainable chemical feedstock of the future. The chemistry of syngas, a mixture of carbon monoxide (CO) and hydrogen, is very well understood and has long been used in the chemical industry as a fuel and feedstock. The production of elaborate chemical structures from syngas requires complex, sometimes energy-intensive processes and, as such, the use of syngas as a feedstock has not been fully exploited. The design of new catalysts and processes could deliver significant advancements (see Chapter Two: CO_2 Capture, Activation and Use, for the production of syngas from CO_2).

How will materials chemistry help?

- Materials chemists will design and optimise selective and robust catalysts (see Chapter Five: Green Materials and Processes) for efficiently and selectively producing new high-value, functionalised products from syngas with low energy input.

Methane as a feedstock

Methane can be used as a fuel and as a chemical feedstock. It is the principal constituent of natural gas, and can also be produced from syngas. It can also be collected from landfills. Methane often surfaces in conjunction with oil drilling which occurs in remote areas; consequently it is often flared off or re-injected rather than collected and used. Sustainable routes to high-value products from methane are required (see Chapter Two: CO_2 Capture, Activation and Use, for production of methane from CO_2).

How will materials chemistry help?

- Materials chemists will design and optimise efficient and selective new catalysts for converting methane to liquids such as methanol, which can be used as a fuel, converted to gasoline, or used as a building block in the chemical industry
- Materials chemists will develop and optimise efficient and selective methods for the direct catalytic conversion of methane to higher hydrocarbons.

Biological feedstocks

Biological feedstocks (from living or recently living organisms) may help to reduce our fossil fuel dependency in the long term by providing biomass for fuels and chemical feedstocks. Sources of biomass, however, must not compete with the crops required to provide food for an increasing world population.[5] It is important that any process to produce chemicals or fuels from biomass is subjected to a full lifecycle analysis[28] before being commercially developed. Sustainable processing of non-food crops,[‡] agricultural waste or marine biomass such as algae, could deliver both fuels and chemicals.

The use of biomass as a feedstock offers the opportunity to exploit the molecular complexity that exists in nature. Such complexity could greatly enhance the practical uses of chemicals available from biomass. With the development of new efficient catalytic processes, the manufacture of these products could be more sustainable than their synthesis from oil.

Bacterial processes could be improved to provide useful chemical feedstocks from biomass. Industrial processes exist to convert corn syrup into high-value polymer components using genetically modified bacteria. However, the efficient separation of chemicals produced from the salty fermentation mixture is a challenge. As a result, energy-intensive purification steps, in addition to large water requirements, can negate possible savings achievable by this route. Technological advances could deliver improved processes which use less energy and water than conventional procedures from petrochemicals.

[‡] Non-food crops such as switchgrass or *Miscanthus* and the robust, high oil-yielding *Euphorbiaceae* family of plants are a source of biological feedstocks that require minimal cultivation.

How will materials chemistry help?

- Materials chemists, biotechnologists and process engineers will develop and optimise new methods to enable the selective separation and conversion of recalcitrant lignocellulosic (woody) and other feedstocks into commodity chemicals, polymers, and fuels.
- Materials chemists will devise and implement solutions that allow the retention of inherent nanostructures, to deliver more highly functionalised compounds from biomass.
- Materials chemists will design more active and selective catalytic or chemical methods to separate and utilise entire biomass-derived materials completely and efficiently.[29]

Biopolymers with enhanced performance

The performance of biologically-derived polymers is often less desirable than those produced from petrochemicals. Extensive research and development will be required to improve currently-available materials. Collaboration between materials chemists, biotechnologists and engineers will enable new high-value products to be designed from existing bio-feedstocks and new, improved crops to be developed.[7,8]

New biologically-derived polymers can be designed that are biodegradable, with thermal and mechanical performance that is competitive with conventional petrochemical-based plastics.[30]

In the first development stages, biologically-derived polymers will likely complement petrochemical-based plastics rather than directly compete with them. In the longer-term, however, biologically-derived plastics could be utilised to produce higher-value products where a cost premium is justified for additional functionality. Scientific advances in current technologies are necessary to achieve replacement of petrochemical products on a broad scale.

How will materials chemistry help?

- Materials chemists will design new, high-efficiency, highly selective catalysts for polymer production from biological feedstocks.
- Materials chemists, biotechnologists and engineers will collaborate to develop new copolymers, modified biopolymers, (nano)composites and blends for new materials, and improved crops for new biologically-derived polymers.
- Materials chemists will improve our understanding of structure/property relationships to better tailor plastics for different applications.

CO_2 as a feedstock

Sustainable production of high-value chemicals, plastics and fuels from CO_2 is a scientifically and technologically feasible goal (see Chapter Two: CO_2 Capture, Activation and Use). New methods to incorporate CO_2 into the supply chain must be sustainable and cost-effective.

4. CONSERVATION OF SCARCE NATURAL RESOURCES

Supplies of scarce natural resources are dwindling at an alarming rate and many vital, rare minerals are often obtained from politically turbulent countries. Shortages will hit within a generation. Materials chemistry can help to reduce, replace and recycle the use of scarce natural resources. New methods to extract phosphorus from soil, rivers and oceans can be developed. Alternative energy storage technologies can be designed that do not rely on supplies of lithium. Materials chemists will design new catalytic processes that do not require platinum, together with new materials for appliances and solar cells that are free from indium. Alternatives to rare earth metals in a range of applications should also be considered. A concerted global strategy to optimise the supply of scarce natural resources is urgently required in the interim, until technological alternatives can be delivered.

The Challenge

Metals and other minerals are essential to almost every aspect of modern life. Phosphorus (P) is one of the main constituents of fertiliser, in the form of phosphates, and is necessary to life through incorporation into DNA and bones. Without supplies of phosphorus it would be impossible to live – it is an essential element. Metals such as lithium (Li), platinum (Pt), palladium (Pd), indium (In) and rare earth metals (a collection of 17 chemical elements) are used in a variety of applications such as batteries, catalysts to facilitate complex chemical transformations (including the removal of pollutants from the air), components for computers, solar cells and mobile phones, and in magnets for motors such as those in wind turbines. The use of many scarce elements in catalysts enables industrial processes to operate efficiently at lower temperatures and with less energy.

The total stock of elemental resources in the Earth's crust is finite, but may be large. A 'reserve' is the stock of metal for which the location and tonnage is known and which can be extracted economically using existing technology. As such, reserves of an element typically represent a small fraction of the total amount in the Earth's crust. Unlike fossil fuels, which are converted to CO_2 and water when burned, elemental resources are not destroyed and can often be recycled and reused. However, efficient recycling depends critically on product design to enable elemental resources to be recovered at the end of a product lifecycle.

Decreasing world supplies of elemental resources is a reality and a potentially more pressing concern than the decreasing supply of oil.[31] It is likely that known reserves of phosphate minerals, for instance, will be depleted within the next 30–100 years.[32] It is a national security concern for many nations that a small group of countries control the remaining stocks of many precious and vital resources. National policies restricting export of certain minerals are already being put into practice. Limited availability and high prices of scarce natural resources will quickly start to affect industries across many different sectors.

Materials chemistry can provide ways to reduce, replace and recycle the use of scarce natural resources. New solutions can be developed to replace scarce elements in technologies and processes with more abundant materials. These solutions should be sustainable – we must not initiate a dependency on other resources that may be in short supply in the future.[33]

Legislation to regulate the supply and use of scarce natural resources must be applied in the short term. However, it is vital that these measures be complemented by support for research and development of sustainable technologies in the medium to long term. We must act now if we are to be able to respond when shortages occur.

Security of carbon feedstocks such as petrochemicals is also of concern. This is discussed in Chapter Three: Fossil Fuel and Feedstock Replacement Materials.

Phosphorus

Technological breakthroughs to guarantee supplies of phosphorus for the survival of future generations are needed. There is currently no practical method of ensuring a supply of phosphorus without a steady supply of phosphate minerals. Phosphorus is present in soil, rivers and oceans, often originating from fertiliser run-offs. There is potential to extract phosphorus from these sources, however there are physical and energetic barriers limiting the development of such processes. Fundamental research is urgently required to develop sustainable solutions.

How will materials chemistry help?

- Materials chemists will conceive of and develop new materials that are able to selectively bind to and remove phosphorus-containing species such as phosphate from water and soil using host-guest and metal coordination chemistry.
- Chemists, engineers and biotechnologists will develop and optimise membrane technologies to selectively concentrate phosphate from water.

Lithium

Lithium is the most commonly used metal in batteries, and will continue to form part of future energy storage technologies in the short to medium term (see Chapter One: Energy Conversion and Storage). Lithium also has important pharmaceutical applications. New technologies to reduce and replace the use of lithium are required.

It is unclear how long known lithium reserves will last. Estimates of the size of lithium deposits that are accessible with existing extraction technologies, together with the rate at which they are being consumed and the threat of reduced supply, suggest that supplies will last around 45 years. This may be shorter if lithium-ion batteries become more prevalent.[34,35] Although it may be possible to develop improved techniques for recycling lithium from batteries as usage increases, methods to obtain lithium from alternative sources are required.

How will materials chemistry help?

- Materials chemists will investigate the potential replacement of lithium in batteries with sodium sulfide (Na_2S), magnesium, nitrogen-doped graphene[§] or other materials.
- Materials chemists will enhance the efficiency and lifetimes of batteries for longer use – a five- to ten-fold improvement on current lifetimes should be achievable.
- Chemists will investigate new technologies to extract lithium from oceans using main group metal coordination chemistry.

Platinum

Platinum is currently used as a key constituent of low temperature fuel cells (see Chapter One: Energy Conversion and Storage). Leaching of the metal is a common problem in fuel cell applications, resulting in lower efficiencies and a loss of the metal to the surrounding environment. Cheaper, more durable fuel cells, made from a stable supply of earth-abundant raw materials are required.

Platinum is also used in catalysts for diverse and important chemical transformations on a large scale, and in catalytic converters for emissions control. New sustainable catalytic processes based on more abundant chemical elements are required (see Chapter Five: Green Materials and Processes).

How will materials chemistry help?

- Chemists will explore and develop alternatives to platinum in fuel cells which are based on more abundant elements.
- Chemists will explore and develop alternatives to platinum in fuel cells which are based on nanomaterials including nitrogen-doped grapheme.
- Materials chemists will undertake the rational design and realisation of nanoscale multimetallic systems, such as alloys, with favourable catalytic properties.

[§] Graphene is a carbon-based electro-active material composed of a single layer of graphite. Graphene is currently a much-studied material for its interesting physical properties and the 2010 Nobel Prize in Physics was awarded to its discoverers.

Indium

Many current solar cell technologies rely heavily on the use of indium (see Chapter One: Energy Conversion and Storage), as do many components of electronic appliances, for instance flat-screen televisions.

Fundamental materials research could deliver viable alternatives to the use of indium in the next five to ten years.

How will materials chemistry help?

- Materials chemists will research and develop cheaper, more stable supplies of materials for solar cells, organic light-emitting diodes, and for better and cheaper display technologies
- Materials chemists will design and optimise new light- and heat-stable transparent, electrically conducting materials with favourable properties for multiple applications

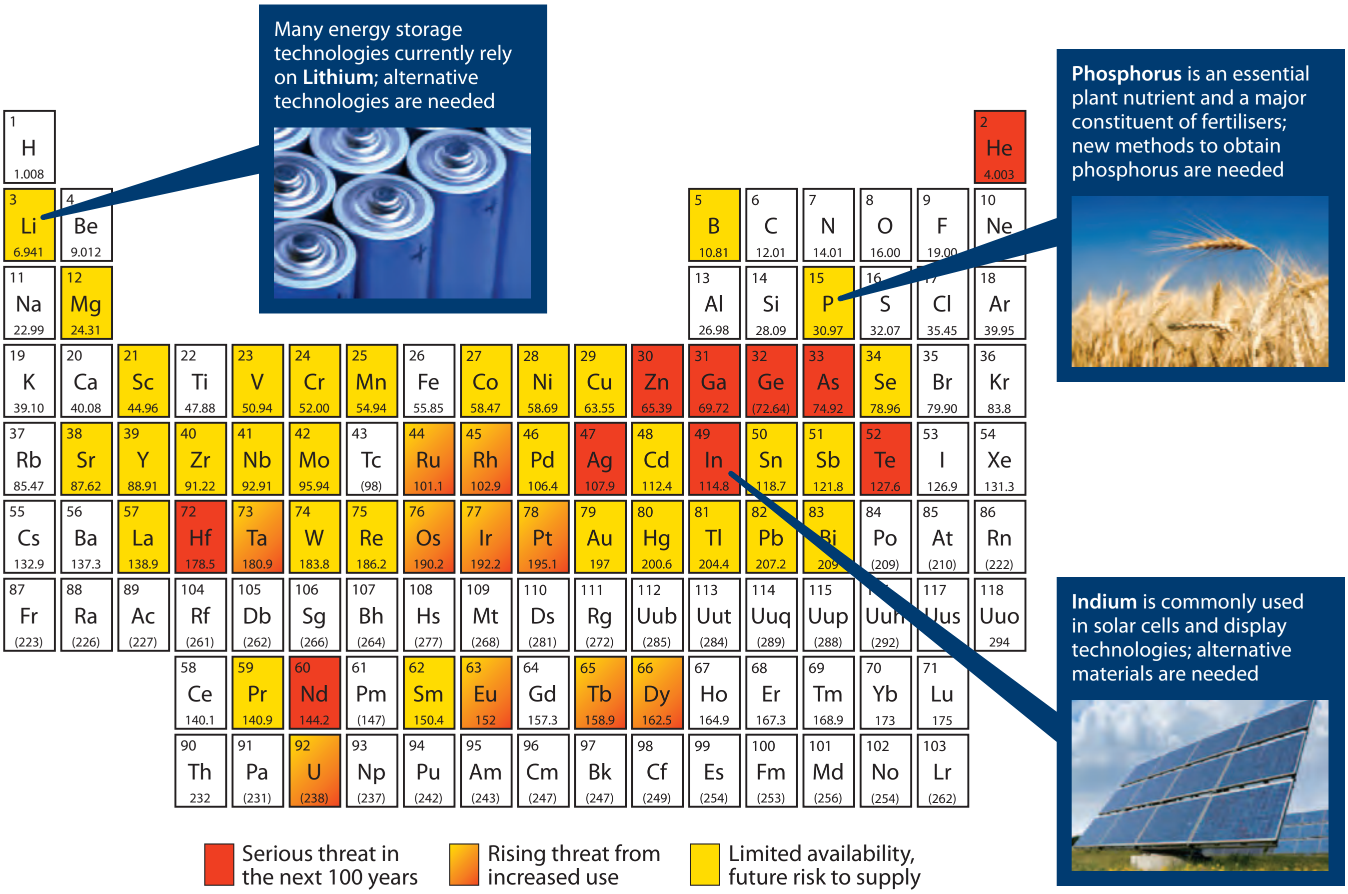
Rare earth metals

Rare earth metals, for example neodymium are used in magnets for many industries and technologies, including the communications and energy sectors.

A stable supply of magnets for a variety of applications is required. With targeted research, the replacement of rare earth metals in magnets may be achieved in less than five years. New technologies to efficiently extract rare earth metals from different sources will be required in the interim.

How will materials chemistry help?

- Materials chemists will enhance our capabilities in the area of rare earth metal magnetic properties, to improve magnet performance and to reduce the rare earth content.
- Materials chemists will enhance our capabilities in the area of rare earth metal coordination chemistry, to facilitate the design of improved capture methods.



Many energy storage technologies currently rely on **Lithium**; alternative technologies are needed

Phosphorus is an essential plant nutrient and a major constituent of fertilisers; new methods to obtain phosphorus are needed

Indium is commonly used in solar cells and display technologies; alternative materials are needed

🟥 Serious threat in the next 100 years

🟧 Rising threat from increased use

🟨 Limited availability, future risk to supply

Figure 4: Endangered elements: the periodic table in short supply[36]

Supply and regulation

Strategies to acquire and regulate the use of scarce natural resources are urgently required. Many countries are now legislating to mitigate the effect of dwindling supplies.

A report produced for the Japanese government in 2007[37] lays down four principles for the use of scarce metals and regulated elements: reduction, replacement, recycling and regulation. On the basis of these principles, Japan has defined its element strategy as one of the most important priorities for science and technology research.

A similar programme began in the EU in 2009,[38] where it has been agreed that information on known reserves of many elements is lacking, and therefore further information should be obtained and catalogued.

In the UK, the House of Commons Science and Technology Select Committee launched an enquiry into strategically important metals in November 2010, and will report to the UK Government in early 2011.[39] Similarly, the US Department of Energy released a report detailing its Critical Materials Strategy in December 2010.[40]

Measures to guarantee appropriate global supplies of scarce natural resources, and to regulate their use, must be replicated in other countries.

5. GREEN MATERIALS AND PROCESSES

The pressures created by a growing world population are damaging the environment. We must meet our energy, material and water needs in ways that are non-harmful and sustainable, using the principles of green chemistry. Materials chemistry can help to develop new catalysts that do not rely on scarce or toxic chemical elements while delivering high yields of product and generating minimal waste. New large-scale industrial processes can be designed that are energy- and water- efficient yet avoid fouling of the environment. New technologies to better monitor and remove air, soil and water pollutants from the environment can be designed for both developing and developed countries. New generations of plastics can be designed that are safe, easily recyclable or fully biodegradable, to have a minimal impact on the environment.

The Challenge

Sustainable and environmentally-benign processes will be required to satisfy human energy, material and water needs as the world population continues to grow. These processes can be designed using the Twelve Principles of Green Chemistry (see Box 1) to deliver significant energy and financial savings. These savings should be an incentive for industries, as well as academic researchers, to invest time and resources in developing new green materials and processes.

Box 1
The Twelve Principles of Green Chemistry:[41]

- prevent waste;
- design safer chemicals and products;
- design less hazardous chemical syntheses;
- use renewable feedstocks;
- use catalysts, not stoichiometric reagents;
- avoid chemical derivatives;
- maximise atom economy;
- use safer solvents and reaction conditions;
- increase energy efficiency;
- design chemicals and products to degrade after use;
- analyse in real time to prevent pollution;
- minimise the potential for accidents.

New and improved catalytic processes are needed that take place at lower temperatures and pressures, and in benign solvents. As already noted in previous discussion, catalysts are able to direct selective chemical processes while significantly reducing the required energy and increasing throughput. Approximately 90% of all chemical products used in our daily lives are produced with the aid of catalysis and, as such, the impact of catalysis on modern society cannot be overstated.[42] New approaches to catalytic process design are required, together with innovative methods, to identify ways to improve industrial-size processes.

Emissions of air, soil and water pollutants remain an issue worldwide, especially in urban areas including highly populated megacities, and plastics continue to pollute our environment. We must act to remove those that are currently present and every effort must be made to avoid the generation of waste in the future. The detection, control and remediation of pollutants in air, water and soil is a prerequisite for a cleaner, more hospitable planet.

There is a growing pressure to design synthetic materials that are produced using sustainable resources, and that have little or no long-term environmental impact, in a world where consumers demand products made from 'natural' materials. Materials chemists can deliver new functional materials, for multiple applications, that meet these demands.

New catalysts

Catalysts make a vital contribution to our daily lives. Applications range from the manufacture of polymers and bulk chemicals (such as ammonia, polyethylene and acetic acid) to the synthesis of pharmaceutical intermediates and catalytic converters for emissions control. Many catalysts in current use are based on scarce elements such as platinum (see Chapter Four: Conservation of Scarce Natural Resources). New catalysts are required that deliver high yields of products, without forming harmful by-products, and that are composed of earth-abundant elements.

Fouling of catalysts and environmental contamination are problems with many current industrial processes. New processes must enable catalysts to be regenerated, and unused starting materials to be recycled.

Catalysts that can effectively utilise chemicals from biomass will be required as alternatives to traditional processes that use petroleum feedstocks (see Chapter Three: Fossil Fuel and Feedstock Replacement Materials). Materials chemists will design families of catalysts for new bio-based feedstocks that function effectively in water, with good levels of efficiency, activity and selectivity.

Immobilised (or anchored) catalysts have the potential to revolutionise many industrial processes. These catalysts are bound to an insoluble solid and therefore easily removed and recycled after use. In this way, drugs and materials can be synthesised in high purity and free from the problem of metal contamination often associated with more traditional catalytic procedures that produce metal-containing wastes. More systematic approaches to the design of new immobilised catalysts are required to facilitate breakthroughs in this area.

Significant breakthroughs in the design of new catalytic processes could be achieved within five to ten years.

How will materials chemistry help?

- Chemists will design and develop new catalysts that can be used in benign solvents such as water, ionic liquids and supercritical CO_2 (see Chapter Two: CO_2 Capture, Activation and Use).
- New catalysts will be designed and optimised, with favourable activity and selectivity that don't require scarce elements.
- Materials chemists will design and optimise new chemical transformations that take place without solvents or in a medium which acts jointly as solvent and catalyst.
- Chemists will design and optimise new catalysts that can convert biomass into new materials to replace petrochemical products (see Chapter Three: Fossil Fuel and Feedstock Replacement Materials).
- Materials chemists will develop systematic and rational approaches to the design of immobilised catalysts such as cluster catalysts and nanoparticles.

Process design

There are several issues associated with increasing the size of chemical processes from pilot to industrial scale. Loss of process efficiency is commonly encountered and identifying appropriate solutions is also a challenge. Manipulating the properties of materials during production for large-scale applications is difficult. Greater control over the physical properties of materials for applications such as large-area solar cells is required.

Commitment from industry leaders will be required to implement new strategies.

How will materials chemistry help?

- Process chemists and engineers will develop intensification techniques that employ bundles of micro-scale units (for example micro-reactors) for large-scale processes, to minimise mass and energy transport limitations which degrade process efficiency.
- Scientists and engineers will develop new molecular-modelling theories and simulation techniques, to design better industrial processes.
- Materials and process chemists will design processes that deliver greater control of the size, shape, morphology, surface structure and porosity of materials.

Detection, management and remediation of pollutants

Air pollutants

Air pollutants continue to cause environmental and health problems in both developing and developed countries (see Box 2). Air pollution sensors for stationary, transportation, and industrial sources of pollution must be developed to better monitor air quality on a continuous basis. Chemists and the chemical industry are already developing innovative technologies to reduce emissions of air pollutants,[43] however further breakthroughs are needed. Means of capturing air pollutants already present in the atmosphere are also required.

Box 2

Common air pollutants:

- Sulfur dioxide (SO_2), a component of acid rain, is produced in various industrial processes. Levels of SO_2 are increasing overall but are decreasing in developed countries due to governmental regulation over the past 30 years.
- Nitrogen oxides (NO_x) are produced from the reaction of nitrogen and oxygen gases in the air during combustion, particularly in motor vehicles, and contribute to smog and acid rain. Emissions of NO_x are increasing throughout the world.[44]
- Black carbon emissions, created from combustion of many materials, contribute to climate change with a magnitude estimated to be similar to that of CO_2.
- Volatile organic compounds (VOCs) can enter the environment from a number of different sources and contribute to both indoor and outdoor air pollution. VOCs can be associated with respiratory, allergic or immune effects in humans.
- Ozone in the upper atmosphere protects the earth by absorbing harmful ultra-violet (UV) radiation. Ozone forms in the lower atmosphere by the reaction of sunlight on air containing hydrocarbons and nitrogen oxides. In the lower atmosphere, ozone is an air pollutant that can have harmful effects on the human respiratory system and plants.

How will materials chemistry help?

- Materials chemists will develop methods for detecting sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and ozone (O_3), and will develop chemical- and size-resolved measurements of particulate matter.
- Materials chemists will aid the design of new industrial and energy conversion processes that do not emit pollutants into the atmosphere including SO_2, NO_x, VOCs, O_3 and particulate matter.
- Materials chemists will design new materials that more effectively remove air pollutants from the environment.

Water pollutants

We need improved processes to monitor and reduce the levels of pollutants entering our water supplies. The United Nations estimates that approximately 1.1 billion people (18% of the world's population) do not have access to safe drinking water.[45,46] Contamination of water supplies can result from both human activity and natural sources.

The water quality issues in developing countries are often very different from those in developed nations. Pollution from arsenic, agricultural and industrial waste, and pharmaceuticals are widespread problems. Technologies to monitor and remediate many known pollutants exist, but need to be robust, portable and inexpensive.[47]

Materials chemistry can help to develop technologies that remove and even utilise pollutants present in water supplies. Solutions could be delivered within a relatively short timescale through multidisciplinary research and with appropriate industrial incentives.

How will materials chemistry help?

- Materials and analytical chemists will develop and optimise sensors for the continuous monitoring of multiple, low-level pollutants in complex environments.
- Scientists and engineers will design and optimise processes to reduce water pollution caused by human activity at the source, including new water-based chemical processes that can be coupled with effective methods for purifying water after use.
- Materials chemists will help to develop and optimise sustainable sorption, membrane and biodegradation technologies for the removal of pollutants from water, both in the environment and from drinking water supplies.
- Materials chemists and process engineers will design and implement new processes for converting organic pollutants in wastewaters to fuels (see Chapter One: Energy Conversion and Storage).

Production of plastics

A sustainable source of plastics will be required as societal needs grow. In some countries, such as India, waste generated by use of non-degradable plastics is of national concern. Even where recycling schemes exist, recycling processes are often resource-inefficient, requiring a large energy input and resulting in loss of material. New biodegradable materials will be made using building blocks derived from biological sources (biomass). More effective recycling systems are also needed.

Biologically-derived plastics in current use can be disruptive in the recycling system as they are difficult to separate from non-degradable plastics. Better societal education and willingness to participate in recycling schemes will facilitate the isolation and reuse/recycling of differently degradable plastics. Good progress is already being made in many countries – the current recycling quota in Germany is 55% by weight; glass, paper and metal is over 90% recycled.[48]

The development of plastics that degrade to useful or harmless products (functional biodegradation) should be a high priority. A greater consideration of the full lifecycle of products is needed to ensure that the materials used have a demonstrably low environmental impact.[28] A product that is derived from biomass is not necessarily 'safe' – all materials with wide application should be innocuous to both the environment and humankind.

In the future, polymers and plastics will be the most popular production material for many objects and components, from packaging to construction to consumer goods. They will be used to create inexpensive products that are durable and safe when in use, and which degrade quickly into innocuous by-products when no longer required.

How will materials chemistry help?

- Materials chemists will design and optimise new biodegradable plastics made from biologically-derived building blocks.
- Chemists, working with engineers, will help to develop and implement new detection systems and separations technologies to ensure that biologically-derived plastics can be recycled without contaminating existing waste streams.
- With the help of materials chemistry, it will be possible to design and commercialise fully-recyclable or degradable materials that have minimal environmental impact.
- Chemists and biotechnologists will help to develop and optimise polymer building blocks, using fermentation or biochemical technologies, which will help reduce the prices of the resulting polymers.

REFERENCES

1 *State of the world's cities 2008/2009: Harmonious Cities,* UN–HABITAT, 2008, http://www.unhabitat.org/pmss/listItemDetails.aspx?publicationID=2562

2 *Human Development Report 2010,* United Nations Development Programme, 2010, http://hdr.undp.org/en/reports/global/hdr2010/

3 *Growth isn't possible: why we need a new economic direction,* New Economics Foundation, January 2010, http://www.neweconomics.org/publications/growth-isnt-possible

4 *World energy outlook,* International Energy Agency, 2010, www.worldenergyoutlook.org/docs/weo2010/WEO2010_es_english.pdf

5 *The Scientific Century: securing our future prosperity,* Royal Society, March 2010, http://royalsociety.org/The-scientific-century/

6 *Chemistry for Tomorrow's World: a roadmap for the chemical sciences,* Royal Society of Chemistry, July 2009, http://www.rsc.org/ScienceAndTechnology/roadmap/index.asp

7 *Workshop Report: Chemistry for a Sustainable Future,* National Science Foundation Workshop on Sustainability and Chemistry, June 2006, http://www.chem.uiowa.edu/research/sustainability/2009_reprint_chemistry_sustainable_future.pdf

8 *Innovation for a Better Future: Putting Sustainable Chemistry into Action,* SusChem Implementation Action Plan, 2006, http://www.suschem.org/upl/3/default/doc/SusChem_IAP_final(1).pdf

9 *The economic benefits of chemistry research to the UK,* Oxford Economics, September 2010, http://www.rsc.org/ScienceAndTechnology/Policy/Documents/ecobenchem.asp

10 *Global Oil Depletion: an assessment of the evidence for a near-term peak in global oil production,* UK Energy Research Centre, August 2009, www.ukerc.ac.uk/support/tiki-download_file.php?fileId=283

11 *BP Statistical Review of World Energy,* BP, June 2010, http://www.bp.com/statisticalreview

12 *Statistical Release: 2008 UK carbon dioxide emissions for Local Authority and Government Office region level,* UK Department of Energy and Climate Change, September 2010, http://www.decc.gov.uk/assets/decc/Statistics/climate_change/localAuthorityCO2/464-stat-release-2008-uk-co2-emissions.pdf

Web addresses valid March 2011

13 *Powering the World with Sunlight: a white paper describing the discussions and outcomes of the 1st annual Chemical Sciences and Society Summit (CS3),* July 2009, http://www.rsc.org/delivery/_ArticleLinking/DisplayHTMLArticleforfree.cfm?JournalCode=EE&Year=2010&ManuscriptID=b924940k&Iss=2

14 *Energievorsorgung der Zukunft (Summary in English),* December 2009, available from http://www.dechema.de/studien-path-1,123212.html

15 *Enhanced thermoelectric performance of rough silicon nanowires,* Hochbaum, A. I. et al., Nature 451, 163–167, 2008, http://www.nature.com/nature/journal/v451/n7175/abs/nature06381.html

16 *Scaling Up Alternative Energy,* Science Online Special Collection, August 2010, www.sciencemag.org/site/special/energy/

17 *Sun and sand breed Sahara solar power,* New Scientist, 30 November 2010, http://www.newscientist.com/article/dn19785-sun-and-sand-breed-sahara-solar-power.html

18 The Hydrogen Office, Fife, Scotland, http://www.hydrogenoffice.com/

19 *Climate Change 2007: Synthesis Report,* fourth assessment report of the Intergovernmental Panel on Climate Change, 2007, http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm

20 *Clean coal roadmaps to 2030,* IEA Clean Coal Centre, September 2009, http://www.iea-coal.org.uk/publishor/system/component_view.asp?LogDocId=82200&PhyDocID=7212

21 *CO_2 Capture, Transport and Storage,* POSTNOTE 335, Parliamentary Office for Science and Technology (POST), June 2009, http://www.parliament.uk/documents/post/postpn335.pdf

22 *Verwertung und Speicherung von CO_2 (English version),* Dechema, 2009, http://www.dechema.de/studien-path-1,123212.html

23 *The Energy Bill (summary),* UK Department of Energy and Climate Change (DECC), 2010, http://www.decc.gov.uk/assets/decc/legislation/energybill/1_20100226093333_e_@@_energybillfactsheetsummary.pdf

24 *Reversing Global Warming: chemical recycling and utilization of CO_2,* Report of the National Science Foundation-Sponsored Workshop, July 9–10, 2008, http://www.usc.edu/dept/chemistry/loker/ReversingGlobalWarming.pdf

25 *Transformation of Carbon Dioxide,* T. Sakakura, J.-C. Choi, H. Yasuda, Chem. Rev. 107, 2365-2387, 2007, http://onlinelibrary.wiley.com/doi/10.1002/chin.200736261/full

26 *Methanol: The New Hydrogen,* Technology Review, MIT, 2006, http://www.technologyreview.com/BizTech/wtr_16629,296,p1.html

27 *CO_2 as a Refrigerant,* BOC Factsheet, http://www.boconline.co.uk/pdf_downloads/products/products_by_type/r744_co2_refrig_factsheet.pdf

28 *Lifecycle Analysis Review,* Chemistry Innovation Knowledge Transfer Network, 2009, http://www.chemistryinnovation.co.uk/roadmap/sustainable/files/dox/Lifecycle%20Analysis%20review.pdf

29 *Roadmap der Deutschen Katalyseforschung,* December 2010, http://www.dechema.de/studien-path-1,123212.html

30 Nobuyuki Kawashima in *"Biopolymers",* edited by A. Steinbuchel and Y. Doi, Volume 3, Section 9 "Polylactic Acid" pp-251-274, Wiley, April, 2002.

31 *Scarcity of Minerals: a strategic security issue,* The Hague Centre for Strategic Studies, January 2010, http://strategic-metal.typepad.com/strategic-metal-report/2010/10/scarcity-of-minerals-a-strategic-security-issue.html

32 *The story of phosphorus: Global food security and food for thought,* D. Cordell, J.-O. Drangert, S. White, Global Environmental Change, 2009, 19, 292–305, http://www.agci.org/dB/PDFs/09S2_TCrews_StoryofP.pdf

33 *Rohstoffbasis im Wandel* (English version), December 2010, http://www.dechema.de/studien-path-1,123212.html

34 NIMS-EMC Materials Data for the Environment No.8 Characterization Factor in the Category of the 'Utilization of Material Resource', NIMS, 2007

35 *Element Outlook,* National Institute for Materials Science, http://www.nims.go.jp/publicity/publication/files/element_outlook.pdf

36 *Sustainable Technologies Roadmap,* Chemistry Innovation Knowledge Transfer Network (CIKTN) http://www.chemistryinnovation.co.uk/roadmap/sustainable/roadmap.asp?previd=425&id=426

37 *Strategic Proposal Catalog 2004-2010,* CRDS, JST, 2010,
http://crds.jst.go.jp/output/pdf/contents2010.pdf

38 *Critical Raw Materials for the EU,* European Commission, 2010,
http://ec.europa.eu/enterprise/policies/raw-materials/documents/index_en.htm

39 *Committee announce new inquiry into strategically important metals,* press release, United Kingdom Parliament, 11 November 2010,
http://www.parliament.uk/business/committees/committees-a-z/commons-select/science-and-technology-committee/news/101111-new-inquiry---strategically-important-metals/

40 *Critical Materials Strategy,* US Department of Energy, December 2010,
http://www.energy.gov/news/documents/criticalmaterialsstrategy.pdf

41 *Green Chemistry, Theory and Practice,* Anastas, P. T.; Warner, J. C., Oxford University Press: New York, 1998, p. 30,
http://www.epa.gov/gcc/pubs/principles.html

42 *Roadmap der Deutschen Katalyseforschung,* December 2010,
http://www.dechema.de/studien-path-1,123212.html

43 *Innovations for Greenhouse Gas Emission Reductions,* ICCA, 2009,
http://www.icca-chem.org/ICCADocs/LCA-executive-summary-english1.pdf

44 *Nitrate aerosols today and in 2030: a global simulation including aerosols and tropospheric ozone,* S. E. Bauer, D. Koch, N. Unger, S. M. Metzger, D. T. Shindell, and D. G. Streets, Atmos. Chem. Phys., 2007, 7, 5043–5059,
http://www.atmos-chem-phys.net/7/5043/2007/acp-7-5043-2007.html

45 *Water: A Shared Responsibility: The United Nations World Water Development Report 2,* World Water Assessment Programme: Paris and New York, 2006,
http://unesdoc.unesco.org/images/0014/001444/144409e.pdf

46 *Beyond Scarcity: Power, Poverty and the Global Water Crisis.* Human Development Report 2006: United Nations Development Programme,
http://hdr.undp.org/en/reports/global/hdr2006/

47 *Africa's Water Quality: a chemical science perspective,* Pan Africa Chemistry Network (PACN), 2010,
http://www.rsc.org/images/RSC_PACN_Water_Report_tcm18-176914.pdf

48 Data in http://www.agenda21-treffpunkt.de/daten/muell.htm

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