Sustainable materials

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Materials influence every aspect of the energy system; therefore, as well as developing new materials for energy generation, materials scientists should engage in public debate about the limitations of future innovations and the conservation of existing materials.

> global warming requires action from the global population, not just a few pioneers

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The term 'sustainable development' is used to reflect the concern that we should meet the needs of the present without compromising the ability of future generations to meet their own needs. However, the word 'sustainable' is difficult to define precisely and can indicate many different aspirations about economic well-being, social equity and environmental harm. This rightly reflects a broad human agenda, but the actions required to address these three targets are in some cases unrelated, and in others incompatible. A particular problem created by the conflation of economic and environmental intentions of sustainable development occurs when actions to reduce environmental harm are reported per unit of economic or physical output. If output grows faster than the reduction in harm per unit of output, the total environmental harm grows, and it is the absolute physical effects that will challenge future generations. In this context, this Comment article discusses the environmental concerns of sustainable materials and addresses two questions. First, can new materials be developed that support a more sustainable future? Second, what is the role of existing materials within a more sustainable future?

Environmental sustainability

Concerns about environmental sustainability fall into two categories: the release of harmful substances into the natural environment as a result of human activity, and the exhaustion of the Earth's supply of resources as a result of over-extraction. Concern about the release of harmful substances includes issues related to smog, toxic releases to air, water or soil, acid rain and, more widely, the depletion of the ozone layer and global warming. Concern about resources includes the availability of fresh water, fertile land and the finite supply of mineral stocks.

To date, solutions to problems related to harmful releases have typically been developed once a lobby group has clearly linked the released substance to a specific activity, and a technical alternative has been found. Some resource shortage problems have been resolved when rising prices have triggered new supply or the development of alternative solutions. However, the most challenging environmental problems are those for which there is no foreseeable technical substitute, and these all relate fundamentally to energy: for example, with sufficient energy, we can desalinate water, increase agricultural yields (through irrigation and application of fertilizers), neutralize or capture toxic releases and extract minerals from less concentrated sources.

We are not short of fossil fuels, and although the energy required to extract them may increase, we will not have difficulty in expanding our future supply of energy. However, most of today's energy supply leads to the release of greenhouse gases and as a consequence concern about environmentally sustainable materials should be focused primarily on global warming. The next two sections restate the questions posed in the introduction to focus on the relationship between materials and energy, which is the key driver of global warming.

New materials to improve energy systems

Today's energy system — the broad and connected network of technologies that convert primary energy into human services — is the product of past innovations in materials science. Technologies, including fuel combustion, fuel cells, renewable generation, electricity distribution and storage, and devices such as motors, heaters, and electronics, in which the final forms of energy are used to deliver a service, have all arisen out of materials science research. A large part of the materials science community today could claim to be undertaking research that may improve the energy systems of the future.

However, despite intense efforts to develop new materials, the energy system has, so far, seen relatively little transformation in response to concerns over global warming. Conventional fossil fuels continue to dominate supply, and global demand for energy continues to rise. As yet, deployment of carbon capture and sequestration systems is still in its infancy. Meanwhile, nuclear power is declining, and the deployment of new renewables is still at a small scale relative to total energy requirements.

This lack of transformation ought to be a focus for debate, but such a debate would challenge existing interests: policy makers would like to continue to pursue policies based on economic growth and hence increase the demand for energy, therefore, they may make exaggerated claims for the potential of future "it would be valuable if more materials scientists engage in wider public dialogue"

energy generation from renewable sources; and scientists may overstate the potential of their current work on new energy supply technologies to attract additional funding. A pragmatic discussion of the limits to future material development would therefore be a useful contribution to dampen unrealistic hopes for future supply technologies. For example, absolute physical limits provide some constraint on innovation: best practice steel making operates with energy inputs of around double the chemical energy of the bonds between iron and oxygen in haematite and, as a result, there is little scope to enhance efficiency further, and the Shockley–Queisser limit defines the maximum efficiency of a solar cell with a single p–n junction. Rate limits, such as Fourier's law for heat flow through a material, constrain the speed and efficiency of energy conversion processes, and trade offs provide a further constraint on innovation. For example, the benefit of having an increased yield stress created by the newest high-strength steels is, in practice, traded off against the difficulty of manufacturing products using these low-ductility steels.

Informed discussion about the limits to future innovation would help to rationalize current energy policy and would give higher priority to alternative strategies, such as reducing car size, which would reduce energy demand. These approaches are currently overlooked for fear of public unacceptability but are technically available today, and in the absence of a rapid transformation of the energy system they will be required if ambitious targets for medium term emissions reduction are to be achieved.

Existing materials in future energy systems

If global emissions are to be reduced significantly in the near term then, in the absence of a large-scale option for supplying energy without emissions, the demand for energy must be significantly reduced. Production of bulk materials, particularly steel and cement, dominates global industrial emissions and is highly energy efficient[1]. We use these bulk materials in such high volumes that there are no effective substitutes for them; however, in developed economies, we could continue to live well with much less new material. In many applications, we could make equivalent products with half the mass of bulk materials such as steel, cement, paper, plastic and aluminium, and we could use the resulting products for twice as long. For example, typical multi-story commercial buildings in the United Kingdom are built with double the mass of steel required by European Codes of Practice[2], and although they could last for at least a century, the buildings are replaced, on average, after 40 years. By reducing the demand for these bulk materials, global industrial emissions could be cut significantly.

Broad publicity has been given to the idea that a 'circular' economy, in which materials and components are reused or recycled, will provide a sustainable materials system. However, although this is an excellent strategy to process waste and is already well developed for materials such as steel and aluminium, it is not a panacea. Metal recycling remains energy intensive because scrap must be melted at high temperatures and further energy must be expended on removing unwanted elements from the scrap before or after melting. Also, most existing recycling processes downgrade material quality because it is not possible to control the composition of feedstock as accurately as in primary production. Concrete, ceramics and most composites cannot be recycled effectively, and plastics must be highly sorted for valuable recycling. In addition, the energy required to separate elements from electronic waste streams will often be higher than that for primary production and components can be reused only in products with a slow rate of innovation.

These challenges present an important opportunity for materials research, which at present is attracting insufficient attention. Better management of waste streams combined with innovation in separation and refining processes is possible, potentially lucrative and deserves new attention.

Outlook

The quest for a sustainable future, which as discussed in this Comment article has been described as the quest for a future with controlled global warming, is exceptionally difficult. There is no strong lobby to demand action, the technical substitutes for fossil fuels are not being deployed at a sufficient scale and the 'tragedy of the commons' of global warming requires action from the global population, not just a few pioneers. The contributions of materials science to date in this area have largely focused on the opportunity to change the supply side of the energy system, but it would be valuable if more materials scientists engage in wider public dialogue on this topic. The opportunities for more intelligent use and management of the bulk materials are poorly understood in policy circles, and there is an urgent need for better informed debate about the limits to innovation that constrain future energy generation from renewable sources.

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Competing interests
The author declares no competing interests.