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A crisis in the environment? The impact of polymers and adhesives.

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1. Introduction: an Environmental Crisis?

Polymers and composites in general and particularly "surfaces, interfaces, adhesion" are important and interesting areas of pure science. Investigation the "vanishingly small" interface between materials, and understanding its disproportionate effect on the properties and behaviour of the whole, present a formidable intellectual challenge. For many investigators the close link between the science and its application to engineering and technology adds both to the importance and interest.

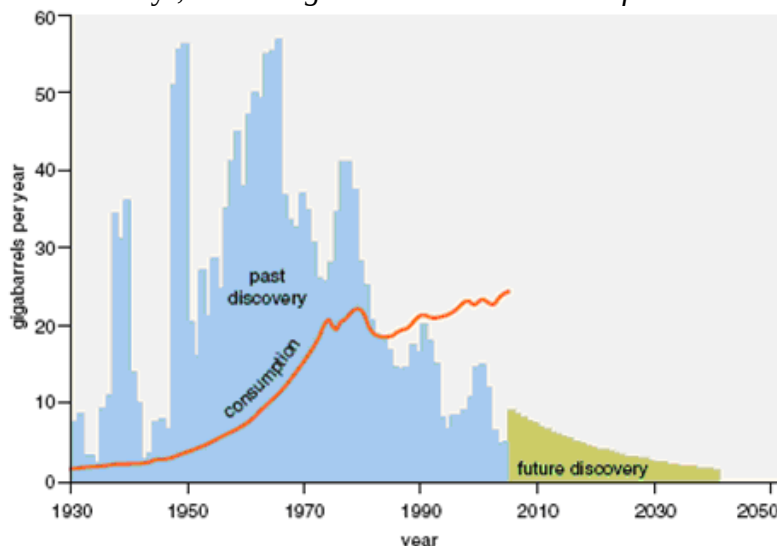
This close link is of great benefit to the industry and has been a major factor in the spectacular growth in plastics production – from 1.5 million tonnes in 1950 to 245 million tonnes in 2008, averaging growth of 9% per annum¹. The link with industry has also benefited science through prestige and research funding. So the science is deeply involved in industrial culture: it shares in its rewards, and also contributes to its problems. High on the list of problems facing contemporary industry are those concerned with the environment.

The broad nature of the environmental problem is well-known, and now widely acknowledged by the scientific community, although still contested by some popular commentators and vested interests. It is associated with the ability of the environment to provide the **resources** needed and its ability to act as a sink for waste materials, **pollutants**.

The polymers and adhesives of contemporary technology overwhelmingly come from fossil fuel sources, especially petroleum. Uncontested figures for petroleum reserves are not available as commercial and political interest makes them matters of intense controversy. However, it is clear that they are finite and running out, even if the precise time-scale is a matter of controversy. Figure 1 contrasts the rate of discovery of oil resources, which appears to have peaked, with the rate of consumption which is still rising².

Figure 1 Rate of discovery and consumption of oil

After Hall and Day², *Revisiting the Limits to Growth After Peak Oil*, 2009.



The production and use of polymers and composites, like most artefacts, rely on **energy** and, most of our energy sources are fossil fuel based. Much work has been undertaken to seek ways around this problem, and there is extensive controversy over the advantages and viability of different putative solutions. It is salutary to bear in mind the enormous differences in the energy return on investment (EROI) associated with various energy sources ^{2, 3, 4}. EROI is the energy gained from a resource divided by the energy used to get that energy. As "easy" energy sources become depleted the EROI on replacement sources tends to be much lower. Reviewing the literature, Murphy and Hall³ found that for drilling for oil and gas in the United States the EROI had declined from about 100:1 in the 1930s, 30:1 in the 1970s, to about 11:1 in 2000. They comment "From this literature we believe that the EROI of our most important fuels is declining over time". The EROI values quoted for "new" energy sources tend to be low, very, very low compared with petroleum in its early days, Table 1. It is apparent that whatever energy sources replace oil, the cheap energy which has underpinned our growth, and has been the basis of most of our industry for the best part of a century will not last for long.

Table 1
Approximate EROI of various energy resources for the United States³.

Resource	EROI
Tar sands	2 to 4
Shale oil	5
Wind turbines	18
photovoltaic	6.8
Ethanol (sugarcane)	0.8 to 10
Ethanol (corn)	0.8 to 1.6
Biodiesel	1.3

The production and use of polymers and composites are also associate with **pollution**. Many consider that the Earth's capacity to carry pollutants is even more pressing a problem than those of depletion of material and energy sources. The most widely discussed pollution problem is the emission of greenhouse gases and consequent climate change. This has the potential not just to cause linear increases in global temperature with extreme meteorological consequences and rises in sea levels, but non-linear chaotic changes which, by their nature are unpredictable and which may be catastrophic ⁵.

Clearly the production and use of polymers, like the majority of industrial processes, are associated with carbon dioxide emissions. In addition, many processes associated with polymers emit volatile organic compounds, which are greenhouse gases and may lead to other pollution problems such as direct toxicity and the production of photochemical smog. Solvents, many additives, pretreatment materials and blowing agents are examples here.

Whether all this constitutes an environmental "crisis" is ultimately a matter of terminology. Suffice it to say that serious scientists* have considered the problem serious enough to speak of the human population's being reduced to "a few breeding pairs" ⁶ and of the 21st as humanity's "final century" ⁷.

2. Polymers, composites, adhesives & the environment

With the enormous increase in the use of polymers, composites and adhesives over the past 50 years, has come an increased environmental impact. However, these materials have often displaced more traditional materials resulting in more elegant, more efficient engineering solutions to design problems. For example, advantages of adhesives over other joining technologies include: better stress distribution over the joint area; the ability to join dissimilar materials; the ability to join thin materials; ease of manufacture, avoiding machining operations for keyways.

While the driving force in the increased use of polymers and composites may not have been environmental, the effect has often been to achieve a "greener" solution. As a symbolic example,

* James Lovelock, CH, CBE, FRS. Professor Martin Lord Rees, O.M., F.R.S., Astronomer Royal, quondam President of the Royal Society and Master of Trinity College, Cambridge.

consider how the technology of carbon fibre composites, aromatic polyamides and other advanced materials enabled the Nuna series of experimental solar cars to travel 3000 km across Australia at average speeds of over 90 km/h, Figure 2 ⁸.

Figure 2
Nuna-4 solar car



Thus the use of polymers and composites has often resulted in a saving in energy and materials and a reduction in toxic emissions associated with the high temperatures and complex chemistry of many metallurgical and ceramic technologies. However environmental problems of resources and pollution remain. Let us examine to what extent these may be addressed, within the context of polymers and composites.

3. Reduction of environmental impact

3.1 Green design principles Environmental impact can be reduced by adopting some fairly obvious design criteria in the practice of chemistry and of engineering. These are sometimes called "green design principles". Thus use of hazardous materials and procedures should be minimised, waste should be avoided and unavoidable pollutants controlled. Renewable resources should be preferred to depleting ones, and the dismantling and recycling at the end of life should be considered at the design stage.

To some extent these "green design principles" are little more than platitudes, but it is of value to make them explicit. Indeed the American Chemical Society's Green Chemistry Institute has formalised them in "Twelve Principles of Green Chemistry" and "Twelve Principles of Green Engineering" ^{9, 10}. These general principles apply, of course, specifically to polymer chemistry and polymer engineering. We will now consider in particular the scope for reducing environmental impact by use of polymers from renewable resources and by recycling waste materials.

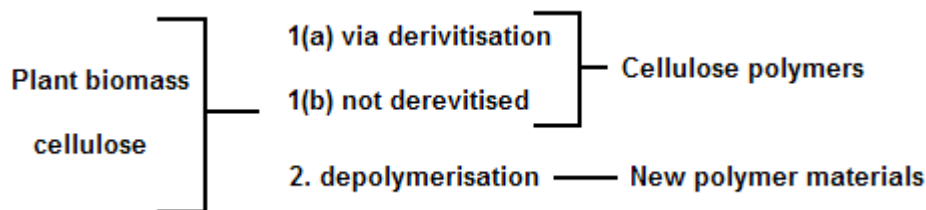
3.2 Polymers from renewable resources. Although the majority of polymers in use come from fossil fuel feedstocks, adhesives and polymers obtained from renewable animal and vegetable sources have long been in use ^{11, 12}. Starch and gelatine-based glues are examples. Natural rubber is an important commercial material and, a rubber plantation is almost as effective as virgin forest in carbon dioxide absorption ¹³.

The pressures to move towards sustainability have stimulated much interest in developing new polymers from plant sources, often using fermentation techniques or genetic modification ^{14 15, 16}. One approach is modify biopolymers as the basis for routes to new polymer materials. Starch, cellulose and chitin are widely available renewable resources and have been used in this way. Alternatively "biorefineries" may be used for converting biological raw materials to industrially valuable intermediates and final products ¹⁷. Clark describes ways in which everyday chemical products, currently obtained from petroleum, could be derived from renewable biomass by fermentation or controlled pyrolysis ¹⁸.

Rose and Palkovits have recently reviewed the uses and potential for cellulose-based polymers ¹⁹. Whereas crops grown as a source for oil and sugar are in direct competition with food crops, in the authors' view lignocellulose biomass, produced by algae and fungi as well as by plants, is not.

The cellulose component of such "plant biomass" may either be processed to produce renewable polymer materials directly, or it may be depolymerised to yield glucose which, in turn is used as a renewable feedstock, see Figure 3.

Figure 3
Routes from cellulose biomass to polymer materials after Rose and Palkovits¹⁹

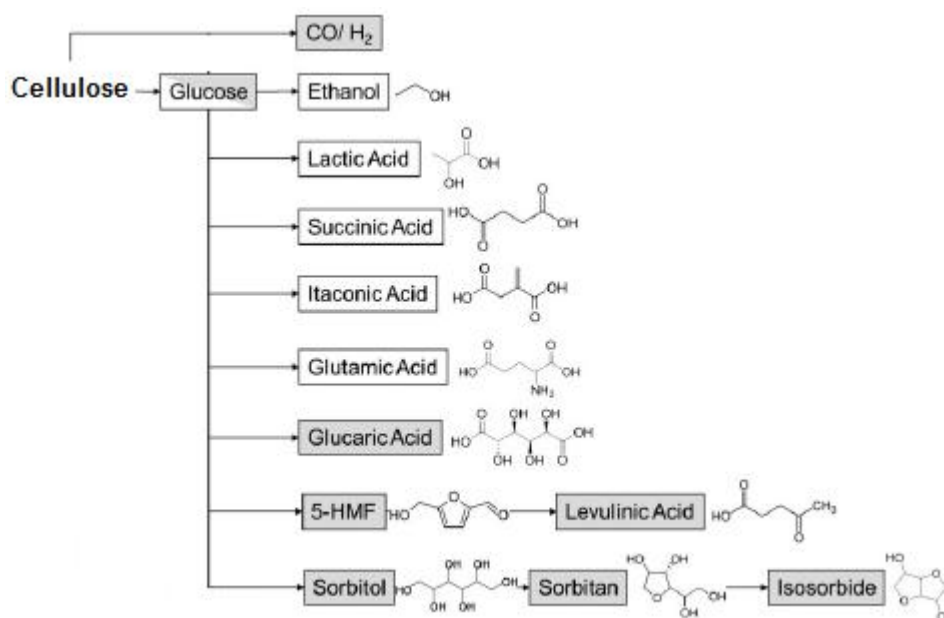


For many years materials have been produced from the cellulose polymer by derivitisation. The long-established route used carbon disulphide in the production of rayon and cellophane. The use of hazardous carbon disulphide is avoided in more recently-developed technologies, for example by employing urea to convert the cellulose to the carbamate.

Cellulose from plant biomass may also be regenerated without derivitisation, for example by the well-known and environmentally unattractive use of Schweizer's reagent – ammoniacal copper hydroxide. Effort in recent years to develop better direct routes to cellulose polymer materials have yet to achieve commercial viability.

An alternative approach, which has considerable potential, is the "biorefinery" route. This uses cellulosic biomass as a route to small molecules which, themselves are capable of further processing to produce useful products. Thermolysis yields synthesis gas (carbon monoxide and hydrogen). Depolymerised by hydrolysis gives glucose whence may be obtained useful organic chemicals including those important in polymer technology. Some are shown in Figure 4. Ethanol is a route to ethylene and to polymers derived from that. Lactic acid can be processed to yield acrylates as well as polyesters, polycarbonate and polyurethanes. Rose and Palkovits discuss such transformations at length.

Figure 4
Scheme for transformation of cellulose to chemicals with potential for future polymer production via biocatalytic (white) or chemocatalytic (grey) transformations¹⁹



Lactic acid, $\text{CH}_3\text{CH}(\text{OH})\text{COOH}$, may also be polymerised to give polylactic acid, also known as polylactide. This is a polyester which may be produced as a fibre, with properties comparable with those of polyethylene terephthalate¹⁴ (Table 2). The two fibres are compared in Table 3 which also shows the carbon dioxide emitted and energy required in their production¹⁴. It is important to recognise that energy is required, and that greenhouse gases are often emitted, in the production of biopolymers, as shown here for polylactide.

Table 2
Comparison of polylactide and melt-spun polylactide fibres with polypropylene, poly(ethyleneterephthalate) and nylon-6

Indexes	Fibres (thread)			
	polylactide	polypropylene	poly(ethylene terephthalate) Laysan)	aliphatic polyamide (capron, nylon 6)
Properties of polymer				
Density, g/cm ³	1.27	0.92	1.38	1.14
Temperature, °C				
melting point	175-180	175	265	214
glass transition	55-60	-(12-20)	90-100	40-45
Moisture content, * %	0.5	0	0.4	4.5
Heat value, kJ/kg	19000	40000	23000	31000
Properties of fibres (thread)				
Deformation modulus, MPa	4000-6000	2000-3500	4000-8000	2000-4000
Strength, cN/tex	40-55	35-50	35-50	35-50
Elongation at break, %	30-40	40-60	30-50	40-50
Elastic restoration, ** %	64	98-100	60-65	95-98

*In standard conditions. ** At 10% initial deformation.

Table 3
Comparison of polylactide and poly(ethyleneterephthalate) fibres

Process or indexes	Poly lactide fibres	Poly(ethylene terephthalate) fibres
Initial raw material	Renewable plant raw material containing hexosans	Nonrenewable resources — petroleum products
Monomer production	Biotech methods, exothermic processes. Heat must be removed	Chemical engineering methods, endothermic processes. Heat must be supplied
Polymer production	Polycondensation in melt at 200-220°C	Polycondensation in melt at 280 -300°C
Fibre and filament production	Melt spinning at 210-220°C followed by drawing and heat treatment	Melt spinning at 280-290°C followed by drawing and heat treatment
Textile production	Usual processes	
Energy consumption, * MJ/kg	92	143
Liberation of CO ₂ into the atmosphere, * kg/kg	4.1-6.5	8.9-12.2

*Data for the entire process cycle, including production of monomer, polymer, and fibre.

Table 4
Polyhydroxybutyrate (PHA) and polyhydroxyoctanoate (PHO) compared with polypropylene (PP)^{14, 20}.

	PHB	PHO	PP
Melting point (deg. C)	180	61	176
Glass transition temp. (deg. C)	5	-35	-10
Molecular weight (kDa)	500-2000	130	200
Density (g/cm ³)	1.18 – 1.25	1.02	0.905
Crystallinity (%)	70	25	70
Oxygen permeability (cm ³ m ⁻² atom ⁻¹ day ⁻¹)	45	-	1700
Water vapour transmission (g m ⁻² day ⁻¹)	60 - 70	-	-
Young's modulus (MPa)	3500	8	1700
Tensile strength (MPa)	40	9	38
Extension to break (%)	5	380	400

Polylactide is an example of a polyhydroxyalkanoate (PHA), many of which are produced within the cells of many different prokaryotic micro-organisms. PHAs are potential alternatives to

polyesters from petroleum sources^[21]. Depending on the length and structure of the alkyl chain they have properties ranging from those of crystalline thermoplastics to elastomers. Thus polyhydroxybutyrate (PHB) is a stiff, highly crystalline material, but polyhydroxyoctanoate (PHO) is a rubbery elastomer, Table 4. There are other PHAs which are completely amorphous, tacky substances.

3.3 Recycling Reuse is an important means of conserving material resources. Recycling of polymers, certainly of linear polymers, is in principle possible^{22, 23}. In practice, successive grinding and remoulding may cause thermal degradation to an extent that the properties suffer.

The recycling of adhesives is even more difficult than of polymers in general, as the adhesive is usually a small proportion of a larger artefact all of which should, in principle, be recycled. Indeed, inappropriate choice of adhesive can aggravate the difficulty of recycling the components joined²⁴. However, adhesives may be available which serve their purpose during the life of an article, but may facilitate disassembly when component recycling is required. Increasingly motor manufacturers are expected to design their vehicles so that their materials can be recovered and reused at the end of the car's life. Hutchinson et al. incorporated (unspecified) foaming agents into adhesives for bonding aluminium sheets and showed that by thermal activation of the foaming agent, the adhesive strength fell, which would enable bonded components in an automotive application easily to be separated²⁵.

A further problem in polymer recycling is that feed stock may consist of mixtures of different grades and compounds of the same polymer or, worse, of different polymer types, leading to poor properties because of polymer-polymer incompatibility.

Several technologies are possible for the disposal of mixed plastic waste. These include mechanical recycling, feedstock recycling, incineration with energy recovery and burying, i.e. using landfill. Mechanical recycling involves separation into different types of polymer, grinding, and remoulding into new artefacts. In feedstock recycling the plastic waste is transformed by heat of chemical reaction to hydrocarbons which are then used as chemical feedstock.

Lazarevic et al. have recently published a review of options for the management of mixed plastic waste²⁶. They found more than 50 life-cycle assessment (LCA) studies, and selected ten "high quality" studies for their review. They compared impacts on global warming, acidification, eutrophication and energy use. Their broad conclusion was that where "single polymer plastic waste fractions with little organic contamination are recycled and replace virgin plastic at a ratio of close to 1:1, recycling is generally the environmentally preferred treatment". Feedstock recycling and use of plastics as a fuel in cement kilns was generally preferable to municipal solid waste incineration; landfill was the least preferred choice, except for global warming potential.

Life-cycle assessment (LCA), sometimes called life-cycle analysis, aims to analyse the environmental impacts of a material or technology throughout its life, "from the cradle to the grave". But, as Lazarevic et al. emphasise, its results are not absolute: they depend on the goals and scope chosen for the studies and on key assumptions which have to be made in order to carry out the analysis.

3.4 Life-cycle assessment Thus renewable substitutes for many fossil fuel-based polymers and adhesives are available, or could plausibly be developed. Recycling is not without its problems, but is often practicable. It is, however, prudent to consider the total environmental impact of alternative materials from their production to their disposal. As discussed above, life-cycle assessment provides one approach to this "from the cradle to the grave" assessment.

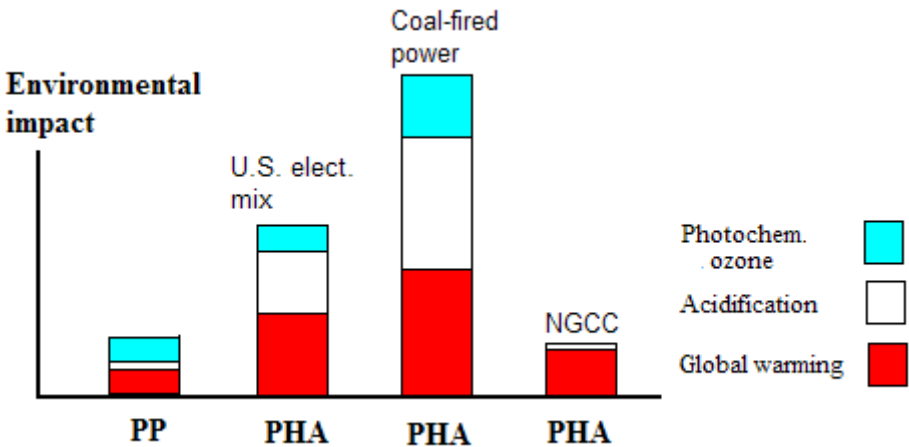
Khoo et al. recently published an example of the use of lca to compare conventional polypropylene carrier bags with ones made from renewable polyhydroxyalkanoate (PHA). This example of simple technology serves to bring out features of significance when considering materials substitution for environmental reasons^{27, 28}.

Khoo and her colleagues chose to compare the impact of the carrier bags as used in Singapore, where they are based. The polypropylene was produced locally from Middle Eastern crude oil; the PHA was produced entirely in the United States, and shipped to Singapore. They considered the impacts of production and disposal separately, and quantified the impacts on global warming, acidification and production of photochemical ozone which were associated with the production of a "standard bag" of each material. The various impacts were normalised by dividing by the

normalisation value (the total impact in Singapore per person per year). The normalised values of various impacts were then *added* to give a figure to represent the total environmental impact of each case examined.

Figure 5 shows the impacts resulting from *production* only (sometimes referred to as "*cradle to gate*"). The polypropylene has a much lower impact than the PHA when it is assumed that the electrical energy associated with the PHA reflected the average of the generation technologies presently used in the United States. In contrast coal-fired electricity generation would significantly increase the impact and combined cycle natural gas generation (NGCC) reduce it just below the polypropylene impact level, although the impact on global warming is still greater for the renewable PHA.

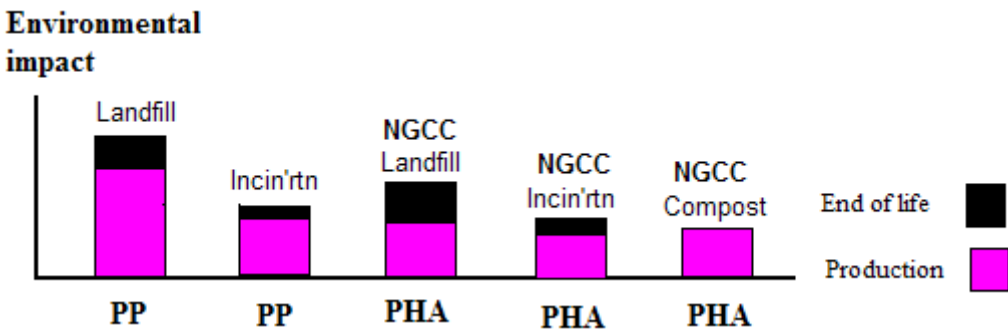
Figure 5
Environmental impact of *production* of carrier bags from polypropylene and poly(hydroxyalkanoate) ²⁷ NGCC = natural gas combined cycle



Disposal of the bags adds to the impacts. Landfill was found to have the highest impact. When incineration was considered the energy recovered was discounted against some of the energy used in production. PHA may be composted, and the compost used as a peat substitute, thus saving greenhouse gas emissions associated with peat production. Figure 6 compares the impacts of the polypropylene bags with those for PHA for the environmentally favourable scenario of energy generation by natural gas combined cycle. In these circumstances the PHA is environmentally comparable with polypropylene, or preferable, if composting is used. Of course, cf. figure 5, with more polluting power generating technologies, the PHA impact is much higher than that for polypropylene.

The authors finish with the obvious, although commonly forgotten point, that multiple reuse of the carrier bags will reduce the unit environmental much more effectively than millions of pounds of clever technology!

Figure 6
Environmental impact of *production and disposal* of carrier bags from polypropylene and poly(hydroxyalkanoate) ²⁸ NGCC = natural gas combined cycle



A study by Tabone et al., published in 2010, considered the environmental impact of the production of a wider range of polymers, some from petroleum and some from biological sources ²⁹.

The polymers chosen were compared in two ways: using metrics based on life-cycle assessment and based on "Green Design" principles, discussed above.

The results were complex – there was no clear-cut conclusion that biomass-based polymers were better for the environment. Ranked by "Green Design" criteria polylactic acid (PLA) and PHA come out best of the 12 materials considered. However the LCA results put polyolefins at the top (polypropylene, HDPE and then LDPE). The biopolymers do well in terms of the effect on global warming and fossil fuel depletion, but have higher impacts on criteria such as toxicity and eutrophication, partly resulting from fertiliser and pesticide use. Different production methods for the same biopolymer were found to have significantly different impacts. The authors point out that their LCA study was limited to the *production* of the polymers. Depending on the impacts during use and disposal, the order of merit could well change.

This 2010 paper of Tabone et al. attracted quite a lot of attention. Its conclusions were briefly summarised in Chemical & Engineering News³⁰, and later adverse criticism was published in Environmental Science & Technology^{31, 32, 33}. Much of the criticism was of the details of the LCA procedures followed; Tabone et al. responded pointing to the difficulty of finding strictly comparable LCA input data for biopolymers³⁴.

Whatever the validity of the detailed conclusions, the paper conveys a clear warning against adopting a simple criterion – such as that renewable polymers are "better" for the environment. The conclusions of Khoo's study, discussed above, reinforce this.

4. A technical "fix" for the environmental crisis?

The *argument of the paper so far* has been that the world is facing an environmental crisis. This crisis is concerned with the depletion of non-renewable resources, especially energy resources, and with the planet's ability to act as a sink for the wastes produced, especially for greenhouse gases emitted as a result of economic activity.

Using polymers as examples, it has been argued that science and technology can do much to address these problems. Renewable energy sources and materials may well be preferred, pollution minimised, waste reduced and materials conserved by recycling. These principles of "Green Design" were discussed above *The question remains as to whether however successfully developed these technical solutions may be, their application across the whole of industry will be adequate to solve the crisis.*

Before considering this question, it is crucial to recognise that there are powerful forces which seriously aggravate the crisis. Three will be mentioned. One is the pressure of population growth. Here some sort of relief may be anticipated. At present the global population is 7000 million, but on the 2004 United Nations medium projection it is expected to peak around 9200 million about 2070, but caution is necessary: the high growth scenario gives 14000 million by 2100 with steep rises thereafter³⁵.

Another of the powerful forces is ideological (mythical in the educated usage of the word): the Western neo-liberal economic paradigm. This has become near-hegemonic: it treats inputs as if the resources concerned were infinite, and aspires to unlimited growth. This would appear to be difficult to reconcile with the 1st Law of Thermodynamics³⁶. The 2nd Law has equally serious implications: the inputs to the system are typically of low entropy (highly ordered) and the wastes typically of high entropy (disordered), as the 2nd Law predicts. Thus low entropy petroleum is burnt to produce high entropy carbon dioxide and water.

This economic paradigm resonates with the dominant social paradigm (DSP) with its explicit belief in progress, in the sense of a continuously improving material standards of living, and implicit faith in the "technical fix", that science and technology will infallibly provide a way out of our difficulties. This aspiration to ever-increasing material standards of living, of course, aggravates the problem of finite resources and of disposal of pollutants.

5. Energy demand and supply

The question as to whether technical solutions will be adequate to solve the crisis in resources can be addressed by examining likely future demand and supply. Energy, which is central to almost all technology, provides a critical example. In 2008 the global primary energy use was of the order of 514

EJ/yr (1EJ = 1 exajoule = 10^{18} joule), according to International Energy Agency figures³⁷. What will it be in the future?

Estimates of future energy demand are available, and obviously depend upon what assumptions are made about population growth and energy usage. The Intergovernmental Panel on Climate Change in 2007 reviewed a wide range of predictions of primary energy requirements, drawing attention to the assumptions on which they were based and the greenhouse gas emissions which they implied³⁸. Estimates of future demands for global primary energy in a broadly "*business as usual*" world, i.e. in the absence of policy change or major supply constraints with consequent increases in oil demand and CO₂ emissions have been made by the Energy Information Administration and the International Energy Agency³⁷. These suggest that the energy supply needed to meet the demand in 2050 is likely to be in the vicinity of 1000 EJ/yr. and that the cumulative global primary energy requirement from 2005 to 2050 is about 30,000 EJ³⁹.

Trainer⁴⁰ has recently considered how an energy supply of 1000 EJ/yr, required in 2050, might be provided in a way which was consistent with meeting safe greenhouse emission targets. His analysis assumes that there will be a 33% increased in energy efficiency by 2050. It emphasises that the output of many renewable generation technologies has a strong seasonal variability and an inherent intermittency. This means that there must be considerable "redundancy" in the provision of generating plant if a steady supply is to be maintained. Trainer argues that "It is not likely that energy-intensive economies could sustain the required multiples of present investment indicated". Put more prosaically, his conclusion is that the energy requirement implicit in a broadly "business as usual" world development scenario is inconsistent with a safe level of greenhouse emission.

So far we have been considering a "business as usual" scenario. Trainer⁴⁰ further points out that the 1000 EJ/yr primary energy requirement, which he used for the 2050 illustration, would be well below that needed to provide energy equity to the whole world. A simple calculation shows that if the expected (United Nations 2004 medium projection) world population in 2050 of 9000 million were to consume energy at the present per caput rate of the Western world, something in the region of 4000 EJ/yr would be needed. Some of these energy figures are compared in Table 5(a).

A similar problem with "business as usual" world development scenarios emerges when the cumulative primary energy demand is compared with published reserves for oil, natural gas and uranium. Figures for such reserves are intrinsically imprecise, a problem compounded by governmental and commercial secrecy. Recognising this, Turner⁴¹ argued that the lower bound for ultimate resources of primary was about 60,000 EJ, the upper bound (including low grade coal) roughly two to three times as great. Some of Turner's figures are given in Table 5(b).

Table 5(a)
Actual and projected global primary energy requirements

Scenario	Global primary energy requirement
Actual in 2008	514 EJ/yr
"Business as usual" in 2050	1000 EJ/yr
Global energy equity in 2050	5000 EJ/yr
"Business as usual" cumulative 2005 to 2050	30,000 EJ

Table 5(b)
Some estimates of global energy resources from Turner⁴¹

Fuel	Ultimate resource EJ
Conventional oil	10,000
Conventional gas	10,000 - 20,000
Non-conventional oil	10,000 - 40,000
Non-conventional gas	20,000
Nuclear fission	5,000 – 9,500

6. The Stationary State – Limits to Growth

Thus there are good reasons to question the plausibility of energy resources being sufficient to allow "business as usual" economic growth for the foreseeable future. The difficulties are compounded when the need to reduce greenhouse gas emissions to a safe level is recognised. This is essentially the

argument that there are "limits to growth", which has long been made, and is implicit in the Laws of Thermodynamics. The eighteenth century moral philosopher, Adam Smith, often called the "Father of Economics", recognised that economic growth would eventually reach limits in a "stationary state"^{42, 43}. John Stuart Mill⁴⁴ insisted, in his influential *Principles of Political Economy* (1848, revised 1873),

It must always have been seen, more or less distinctly, by political economists, that the increase of wealth is not boundless: that at the end of what they term the progressive state lies the stationary state, that all progress in wealth is but a postponement of this, and that each step in advance is an approach to it.

The famous Club of Rome study "*Limits to Growth*" published in 1972 revived interest in the stationary state⁴⁵. It showed that, if unchecked, exponential growth in population and in resource use, together with the finite capacity for the assimilation of pollution would lead to a serious collapse in the material quality of life and human population during the first half of the present century.

The study challenged the dominant economic and social paradigms, causing intense controversy: it was widely denigrated and often misrepresented^{41, 46}. However, 30 years on from the original Limits to Growth study, it can be seen⁴¹ that the predictions of its "business as usual" scenario compare well – so far – with historic data between 1970 and 2000. Whether collapse will occur midway through the 21st century, in accordance with the scenario output, remains to be seen.

These philosophical and practical considerations clearly call into question the validity and continuing utility of the Dominant Social Paradigm with its belief in progress (material standards of living will continuously improve) and that scientific advance will always provide solutions to our problems. Such beliefs form a narrative which has become firmly embedded in the popular consciousness in Western industrial society; it is supported by a host of powerful vested interests, and is now increasingly adopted on a global scale. However it is important to recognise that this narrative does not represent some sort of "unchanging Law of Nature". Historically speaking it is recent: its origin can be traced to the ideas of the Enlightenment in eighteenth century Europe⁴⁷. When such narratives cease to be useful in helping the human race to understand its position in the world, they must be developed or replaced.

One such development is outlined in the paper published by the U. K. Government's Sustainable Development Commission entitled *Prosperity without growth? The transition to a sustainable economy*^{48, 49}. This points to the fundamental problem with an economic system which does not adequately take into account the finite nature of many resources and the degradation of ecosystems by pollution. It argues for a much broader concept of human wellbeing than one which focuses exclusively on continual growth in material prosperity, and calls for a fundamental restructuring of the financial system and a basic rethinking of the economy, setting out a route to a sustainability. The social transformation implicit in such a change have recently been elaborated⁵⁰.

Tim Jackson, the Economics Commissioner at the Sustainable Development Commission, terms economic progress a "myth", using the word to depict a conceptual framework which provides ways of thinking about the world. He points out that "every society clings to a myth by which it lives; ours is the myth of economic progress but a society that allows itself to be steered by a faulty myth risks foundering on the shores of harsh reality"⁵¹.

Such ideas, of course, challenge powerful vested interests[⊕].

7. Conclusions

Since the middle of the last century the global economy has grown by a factor of about five. Cheap and abundant oil and gas have favoured growth in general and, particularly, in the polymer and adhesives industries. These industries, then, have played a part in generating the present prosperity and the present environmental crisis of resources (especially of energy resources) and of pollution (especially of greenhouse gas emissions.) By adopting the principles of "green chemistry and engineering" much can be done by replacing the use of limited resources by use of renewable resources and to reduce polluting emissions. However it is important that these principles are used critically: it is entirely possible, for example, that the substitution of a biopolymer for one based on

[⊕] The Sustainable Development Commission was closed by the new Conservative-led government on 31st March 2011.

petroleum will lead to an increased environmental impact. Quantitative assessment, such as detailed "cradle to grave" life-cycle analysis is needed.

It might seem that the thorough, but critical, use of "green chemistry and engineering" principles would provide a resolution of the environmental crisis. However the social and economic context is one which strongly adheres to a paradigm of continuous growth. There are good reasons, including those based on the Laws of Thermodynamics, for considering that there are limits to growth and that a social paradigm which ignores these limits is in danger of "foundering on the shores of harsh reality". "Every society clings to a myth by which it lives; ours is the myth of economic progress". Are we ready to recognise that continuous growth is not an immutable Law of Nature, but a myth (according to the educated usage of the word) which may have served us well in the past but which now must be significantly modified?

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