Innovation, plastics and the merits of carbon

The West has lost the plot in innovation – but the whole world needs to rehabilitate 'stuff', plastics and the sixth element in the periodic table

Russia is different from the West. Yet even in Russia, and certainly in India and China, the West's fashionable hostility to material wealth, to goods and to economic growth may be growing among the middle classes.

In the West, you can see it very early on, in *The Graduate* (1967), the famous film of Mike Nichols, who just died. In that film, an executive tries to suggest to the young, 1960s-ish Dustin Hoffman, that his future career should be centred around something he is already suspicious of: plastics. So by now, it should be no surprise that books have been published in America, Australia and Britain on the subject of what they call 'affluenza', the nasty and even infectious side-effects of owning too much stuff. Since 2011, indeed, two American corporate high-flyers, Joshua Fields Millburn and Ryan Nicodemus, have together penned no fewer than seven books on so-called minimalist consumer habits – quite a feat of trees-to-paper consumption in itself. Equally, the London-based futurologist James Wallman has popularised the idea of 'stuffocation' – the feeling you get 'when you look in your wardrobe and it's bursting with clothes but you can't find a thing to wear'.

Yet most of the world is not bursting with too much choice. In this light, the plastics industry now needs to rally to the defence of 'stuff'. And, to advance its efforts in innovation, Russia needs to recognise the manufacturing advantages that it could reap from its rich endowment of hydrocarbons.

The world's manufacturing sector has lately begun to chalk up impressive advances. Do these advances amount to what Peter Marsh, an encyclopaedic English analyst of manufacturing, terms 'the new industrial revolution'? Do these advances presage what he calls 'the end' of mass production? Hardly. Yet whatever setbacks they are likely to face over the next 10 years, scientific, technological and economic developments promise a world of cheaper, more sophisticated products than the ones available today. Instead of heaping yet more scorn on manufacturing, Russia should take the lead in arguing that there is much that manufacturing – not least, with plastics, and with carbon more generally – has to offer, both for humanity and for progress.

Product autonomy through printable, light, strong and stiff materials

At a fine Royal Academy of Engineering seminar in London late last year, I was struck by the magic of carbon fibre (developed in 1958), carbon nanotubes (CNTs, popularised by NEC Corporation's Sumio Iijima in Japan 1991), one-atom-thick graphene (produced by Andre Geim and Konstantin Novoselov, two Russians, at the University of Manchester in 2004), and the prospect of artificial human tissue and bone through 'synthetic biology'. Here, stiff, high-strength-to-weight materials are gaining new applications.

Carbon fibre can now be printed like plastics, yet remain tougher than aluminium. Or, take graphene. 'Large area' graphene is now being used in displays, sensors, optics, flexible electronics and flexible solar panels. 'Flake' graphene lends itself to batteries, supercapacitors, food and drink packaging, and membranes for the desalination of water and the purification of fluids. Through graphene, mankind has gained better ways of conducting electricity and heat, as well as new knowledge of what all kinds of materials can do when in the form of 2D layers.

There is more. Anti-reflective coatings for metals, polymers and glass are now self-cleaning, self-healing, anti-bacterial, anti-fogging and water-repellent.

Materials, like machines, will never be truly 'intelligent' or 'smart'. Yet, in their development, they attest to great human ingenuity. In solar panels, we can mix the low cost and flexibility of polymer-based films with stable inorganic nanostructures. That could push us on to punchier, longer-lasting, fourth-generation photovoltaics. In synthetic biology, modular principles and the insertion of genetic codes into microbes have brought new plastics and new varieties of yeast, as well as collagen and magnetically controlled bacteria. Another opportunity lies in synthetic versions of the proteins that go to make up spider silk. These proteins will help in the manufacture of cables, bulletproof vests, wound patches and artificial tendons.

The materials being developed today make for less human labour and more useful products. And, contrary to environmentalists' fears about 'stuff' bringing about resource depletion, supplies of materials are plentiful. Hydrocarbons, essential feedstock to plastics, are every year the subject of new discoveries (1).

While printed electronics ‘functionalise’ product surfaces, plastics has many vital tasks still to undertake

3D printing has been the subject of unbridled hype. Yet, when 3D is put to work to print electronic components on product surfaces, it remains a powerful technique – and one which confirms the possibility of a renaissance in manufacturing. Thermo-electric and solar energy, LED lighting, sensors in home appliances, responsive packaging and labelling, wearable devices and high-efficiency, colour-tunable displays: all these things will benefit from printed electronics.

In Bremen, north Germany, the Fraunhofer Institute has installed a robot production line with all kinds of printing heads – silk-screen, inkjet, dispenser, and aerosol-jet – to dispatch, feed, print and heat-treat, in furnaces, multilayer circuits of varying thickness, as well as sensors that can register factors like temperature and strain. The line prints not just in metals, ceramics, but also in electrically conductive polymers, proteins and enzymes, and on to glass, textiles, metals, ceramic plates, car bodies, windowpanes and other building components.

This is all good news. At the same time, when we look around the world, plastics has many vital tasks still to undertake:

1) As Russia knows, the world’s *pipelines* – not just for gas, but for oil, and water too – are now more significant than ever. Yet when we look at the technology that President Putin is acknowledged to know very well, it remains quite backward. Metal, rust, temporary lash-ups and leaks predominate. The human interface around pipeline joins, maintenance, repair and the auditing of the fluid flows inside pipelines is back in the dark ages.

Can’t plastics, and the plastic electronics we have just mentioned, do much to fix this? Can’t Russia, which is expert in pipelines, help lead the way?

2) By United Nations calculations, the world needs to build 4000 *houses* an hour to keep up with the growth in population, let alone to clear its slums. Moreover, housing has long been a particular problem in Russia. In China, however, after the earthquake in Sichuan in 2008, a million plumbed and powered prefabricated homes, schools and hospitals were delivered, much of them made in polystyrene, within six weeks of the disaster. Similarly, Broad Sustainable Building, a Chinese firm, has built, with just 200 workers, a 30-storey, earthquake-resistant, energy-

efficient hotel in Hunan – complete with very pure air –in just 15 Days. http://www.youtube.com/watch?v=Hdpf-MQM9vY

Without slavish imitation, but with the same kind of confidence, Russia could do something similar. Like Britain, it has had its own difficulties with prefabricated bloc of flats before now. But 2015 is different from the Soviet era. We now have new materials, 3D printing, robots, Internet Protocols and a dynamic Chinese manufacturing sector to reckon with. Things could easily be more successful this time around.

Pipelines and houses represent just two of the opportunities facing plastics. There are other, more modest but still significant openings available. Take retailing, a sector in which Russia has advanced dramatically in recent years. Just a year back, Chinese scientists and others based in MIT, Harvard and the US Army Edgewood Chemical Biological Center, Aberdeen, Maryland, used a transparent, foil-like polymer matrix filled with light-scattering silver nanoparticles, which are available commercially, to offer shop windows the chance inexpensively to display transparent projected images that can be viewed at wide angles. http://bit.ly/1yIEhwk

Carbon represents an opportunity, not just a problem

In my view, industrialisation has added to the greenhouse gases of the world and thus to global warming (2). Moreover, CO_2 is the most significant man-made greenhouse gas. Therefore we should move to a low-carbon or zero-carbon world, right?

Not so fast. This simplistic, black-and-white view of carbon is far too prevalent. About 18 per cent of the human body is carbon. Trees and plants, which form a sink for CO_2 and turn it, through photosynthesis, into oxygen, are made of carbon. Coal- and gas-fired power stations that emit CO_2 are not 'dirty', and nor is it right, when referring to CO_2 emissions, to contrast 'dirty' coal with 'cleaner' gas. http://econ.st/1p9dMzT It's time to rescue carbon from its pariah status.

There is widespread hatred for the stuff. In America, the National Resources Defense Council wants to 'stamp out' humanity's carbon footprint, http://amzn.to/1FcV909 even though no two calculators of one's personal footprint have been known to agree. http://bit.ly/1uopHFL Not content with inveighing against 'dirty' energy, Canadian radical Naomi Klein's new book *This* *changes everything* http://amzn.to/1xZHTKN uses the phrase 'carbon-spewing' five times – about roads, container ships, jumbo jets, holidays and China's Pearl River Delta. Away from the vomit, environmentalists want zero-carbon homes, cities and resorts. And there are the websites: http://www.zerocarbonhub.org, http://www.zerocarbonfootprint.co.uk, http://zerocarbonworld.org and so on.

It's all very one-sided. As the Italian chemist Primo Levi reflected in Auschwitz, http://bit.ly/1r9NglO carbon is 'the only element that can bind itself in long stable chains without a great expense of energy, and for life on earth (the only one we know so far) precisely long chains are required. Therefore carbon is the key element of living substance'. The chemistry of carbon (3) gives it a unique versatility, not just in the artificial world, but also, and above all, in the animal, vegetable and – speak it loud! – *human* kingdoms. Not for nothing was the EU's recent Rosetta space mission to one of our solar system's comets http://bit.ly/1FdU6yM dedicated to – and successful at http://bit.ly/1uoxx2m – finding carbon, the source of life on earth.

Carbon reprise: apps in materials, electronics, solar power – and materials again

The applications of pure carbon in the world of materials alone show how wonderful it is. As it happens, Rosetta's lander module, Philae, had a frame, antenna and landing legs made of carbon fibre: on its legs, that meant rods six times lighter than steel, but up to 50 per cent stiffer. http://bit.ly/1Ay8lPb Back on earth, America's Food and Drug Administration last year approved our old carbon-based friend, plastics, for cranial implants: http://bit.ly/1vzE00Z Connecticut's Oxford Performance Materials uses polyetherketoneketone, which is a high-performance thermoplastic, for the job.

In electronics, CNTs are now working closely with graphene. The result: applications that promise to be impressive once they move out of the lab. Carefully aligned single-walled CNTs, when mixed with nitrogen-doped sheets of reduced graphene oxide, can make fibres that can be woven into clothing to act as long-life micro-supercapacitors, so powering wearable medical devices with as much clout as conventional lithium-ion batteries. http://bit.ly/11HAgNl Again in flexible electronics, strong, fast-working CNT circuits can now be doped by another carbon-based material, DMBI, so they can handle fluctuations in power just as well as rigid silicon chips, and can beat bendy but specially formulated plastic electronics on strength and performance. http://bit.ly/1z9TJkZ

CNTs show the myriad roles that carbon can perform. When bonded to graphene, they could make powerful solar cells. http://bit.ly/1uPeZgY There is also the extraordinary news http://bit.ly/1vzNwRN that, at modest temperatures and pressures and with no hairy chemicals, pushing controlled, alternating voltage pulses across single-walled networks of CNTs can enlarge their diameter, give them multiple walls, or turn them into multi-layered nanoribbons of graphene: good for high-conductivity electronics, as well as for reinforcing composites in transport and sports equipment.

Apart from its physics and chemistry, the biology bound up with carbon confirms its technological prowess. From wood and fibre crops, the EU's Bio-based Industries Consortium (BIC) aims http://bit.ly/1uScd8U to develop pulped cellulose – $(C_6H_{10}O_5)n$ – into textiles, films and thermoplastics. It wants to improve the fermentation of crops to make biosurfactants for cleaning, and specialty carbohydrates with applications cheaper than those that already exist in cosmetics and pharmaceuticals. Other BIC projects may create, from new techniques of processing forest products, materials for packaging, papers, fibres and glues, as well as components in construction and cars. Through similar strategies with beet pulp, potato pulp and brewers' spent grain, the BIC also hopes for new paints and coatings, too (4).

Making use of CO_2

The miracles of carbon, whether in nanotubes, layers of graphene, or long-chain molecules, give the lie to environmentalism's absolutist disgust for it. But what verdict should be made about CO_2, the gas? Once again, it isn't an unalloyed evil.

In the US, three companies – Skyonic, Joule and Novomer – are worth tracking over the next few years. http://bit.ly/1rao52t Skyonic combines salt, water and electricity with the emissions from power plants to produce baking soda, hydrochloric acid and bleach. Joule? Deploying genetically engineered bacterial catalysts, it uses modular, scalable converter ponds http://bit.ly/1tchBAS to turn concentrated industrial waste CO_2, non-potable water and sunlight directly into different fuels, including a species of diesel which it claims http://bit.ly/1uPnyby is free of sulphur and aromatic chemicals. Joule believes this process is superior to that which generates fuels from algae. http://bit.ly/1y097RA Last, Novomer has developed metallic catalysts, such as beta-diiminate zinc acetate, that can quickly polymerise CO_2 by bonding it, in pressurised reactors that operate with low temperatures and energy inputs, to small organic molecules called epoxides. http://bit.ly/1zNanYA The outcome: relatively inexpensive and biodegradable plastics (polycarbonates, polyurethanes) that are up to 50 per cent composed of CO_2.

Much more tricky than these kinds of processes is the retrieval of CO_2 from the atmosphere, rather than from industry. Such a process has both advocates http://bit.ly/154ng6K and detractors. http://bit.ly/1BZ6pkD But we shouldn't yet rush to dismiss 'air capture' as eternally difficult and uneconomical to scale up, or – *à la* Naomi Klein – as a falsely comforting distraction from the need to change our lifestyles. Global warming has still left us plenty of years in which to make the technology a viable proposition. (5)

Altogether, CO_2 isn't just a greenhouse gas. It has chemical potential in its own right. Plastics manufacturers need to learn more about what they can do with it.

Toward a New Carbon Infrastructure

Richard Branson's Virgin Earth Challenge http://www.virginearth.com is a competition for air capturers of CO_2 that offers just $25m in prize money. Yet as Klein notes, Branson is on record as saying 'Carbon is the enemy. Let's attack it in any possible way we can, or many people will die just like in any war'. Clearly, hyperbole and alarmism characterise even the can-do camp among those who make global warming their Alpha and their Omega.

The industrial-scale recycling of CO_2, and the harnessing of carbon in all branches of industry, exposes how a messianic – indeed, Manichean – hostility to carbon is a one-sided fraud. In the third paragraph of his monumental book *Capital*, http://bit.ly/1yF1cIW Karl Marx observed that to discover the various uses of things 'is the work of history'. On the whole, then, the world is still in a prehistoric period in relation to carbon. It has yet fully to realise the potential of this most remarkable of atoms.

We will never enter a New Carbon Economy – that phrase too would be hyperbolic, just like The Internet Economy, The Biotech Century and all the rest. But the world could really do with a New Carbon Infrastructure, (6) in which the plastics industry – Russia's included – uses the properties of the element on a truly ambitious scale.

Some Greens like 'organic' farming; yet that irrational cause http://bit.ly/1Az1KnH does not prevent even them from castigating carbon in all its other forms. It's time to get things straight. Even CO_2 need not always be a problem. So let's hear it for carbon!

(1) Whatever the environmentalist hostility to hydrocarbon-based plastics, no environmentalist can deny that hydrocarbon-based plastics save weight and therefore save energy in transport vehicles – including public transport vehicles running on renewable power. The figures for oil and gas reserves are as follows:

Billion barrels of oil

1992	2002	2012	2013
1039.3	1321.5	1668.9	1687.9

Trillion cubic metres of gas

1992	2002	2012	2013
117.6	154.9	185.3	185.7

Source: *BP Statistical review of world energy 2014*, on http://bit.ly/1y581Fb

(2) James Woudhuysen and Joe Kaplinsky, *Energise! A future for energy innovation*, Beautiful Books, 2009.

(3) Although organic, carbon-based chemistry technically excludes the chemistry of pure carbon, in its different allotropes, as well as the chemistry of CO_2, organic compounds form a larger, more variegated domain than the domain of inorganic chemistry. This too is testimony to the power of carbon.

(4) As with British Chancellor George Osborne's budget for research into graphene, which amounts to a princely £60m, http://bit.ly/1uScd8U the monies that the European Commission has promised to make available for the BIC are laughable – just €50m for its current 'work plan' of 16 projects, http://bit.ly/1p9Jj4R and less than €1bn over the whole period 2014-2020. http://bit.ly/1toiiGx

(5) Even if humanity made the decision to allow no new net CO_2 to enter the earth's atmosphere, carbon would still be around, not only as living matter and in the form of engineering materials and components, but as a transport fuel – at least until such time as the energy density of the battery on an electric car rises 100-fold, from 250 kiloJoules per kilo (measured by weight), or 360 kJ/litre (measured by volume), to surpass that offered by petrol: 44,400 kJ/kg or 34,800 kJ/litre. Whether we drill for hydrocarbons or make them ourselves, they will still be indispensable. Indeed, one of the merits of air capture is that, unlike carbon capture and storage around power plants, it can do something about the CO_2 emissions around *transport*, http://bit.ly/1AB51mu which is the source of the fastest-growing emissions today.

(6) James Woudhuysen and Joe Kaplinsky, *Energise! A future for energy innovation*, Beautiful Books, 2009, chapter 5. This chapter, which is devoted to the New Carbon Infrastructure, also cites top American scientists George M Whitesides and George W Crabtree, and their view that little research has been done on the chemistry of CO_2 for decades.