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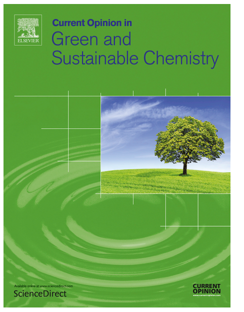

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UN Sustainable Development Goals: how can sustainable/green chemistry contribute? By doing things differently

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Abstract: Until now, much Green and Sustainable Chemistry has been focused on how chemicals are made. Here we suggest that, if chemistry is to contribute effectively to achieving the SDGs, we need to change the way that things are done at both ends of the chemical supply chain. For chemical research at the start of the chain, we need to rethink how we build the laboratories in which we carry out the research so as to minimize the use of energy. At the other end of the chain, we advocate the adoption of a Moore's Law for Chemistry (MLFC), which we recently proposed that, wherever possible, the amount of chemical(s) used to achieve a given effect should be decreased by a factor of 2 every five years.

Keywords: Sustainability; Carbon Neutral Laboratories; Moore's Law; F-factor; Green Chemistry.

There is continuing debate as to the precise origins of Green Chemistry. Undoubtedly some, if not many, of the concepts were first applied in the late 1970s and 1980s [see references 1 to 3]. Indeed, it has been suggested that some of the approach was proposed by Ciamician in his landmark paper over 100 years ago [4]. However, it is also clear that Sheldon's encapsulation of the E-factor (kg of waste/kg of product) [5] and the formalization of the 12 Principles of Green Chemistry by Warner and Anastas [6] gave the field a major boost and greater coherence. These concepts have demonstrably influenced synthetic strategies and manufacturing routes in, for example, the pharmaceutical industry [7, 8] and there is no doubt that the advent of Green Chemistry provided a fresh starting point for many chemists to carry out their work in a more environmentally friendly way. However, there has not yet been a similarly clear trigger point in the development of Sustainable Chemistry.

Green Chemistry focuses particularly on the reduction of risk to human health or more, generally, the health of the environment. Long term sustainability *per* se is not a major goal, although Principle 7 of the 12 Principles of Green Chemistry does state that "*a raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable*". The Brundtland definition of sustainable development [9] as "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*" is clearly inspirational but gives little indication of how chemistry should be made sustainable. Horvath and co-workers' recent papers [10, 11] make interesting suggestions of metrics for judging the sustainability of products and fuels derived by conversion of biomass but again they provide no easily identified goal.

Our planet, however, is faced with a rapidly increasing human population with an associated demand for increased consumption, including an increased consumption of chemicals [12]. At the same time, there is a realisation that the reserves of many of the elements which underpin current chemical and materials manufacturing are depleting at a worrying rate, leading to the concept of “endangered elements” [13], see Figure 1. Such concerns are also leading to an increasing focus on the so- called “circular economy which encourages the design of products specifically to promote recycling [15, 16].

Green and Sustainable Chemistry have had some success in changing attitudes to, and to some extent behaviour in chemical manufacture and production. Indeed, most of the research effort has focused on the invention and development of cleaner chemical processes with reduced environmental impact. However, there has been much less effect in two areas; (i) how chemical research is conducted, and (ii) how we use chemicals once they are produced. It is the thesis of this article that we need to address both of these issues, if we are to succeed in deploying sustainable chemistry to underpin the implementation of the SDGs, and we make suggestions of how we might begin tackling the problems of creating carbon neutral laboratories and of promoting the more sustainable use of chemicals.

Although modern chemical laboratories appear clean and airy compared to the dingy halls of the past, there has usually been little effort to tackle the underlying problem of high energy usage. Fume cupboards still pump large volumes of air out of the buildings and much of instrumentation has not been designed to minimize energy consumption. Of course, there are exceptions of low energy instruments but, as far as we are aware, there have been few attempts to “decarbonize” the entire enterprise of academic chemical research. One exception is the new GSK Carbon Neutral Laboratories, the CNL, built in Nottingham with financial support from the pharma company GSK, the UK Higher Education Funding Council for England and the University of Nottingham.

The CNL, housing chemists and engineers researching in Green and Sustainable Chemistry, is itself an experiment which aims to minimize every aspect of its construction and operation such that it will be totally carbon-neutral within 25 years, less than the planned lifetime of the building, See Figure 2. The whole building is instrumented to monitor different aspects of energy usage and all chemicals and equipment are logged in and out of the building. Construction was completed in June 2016 and the labs have been operation for a little over 18 months. The laboratories are designed for energy efficiency and house state of the art instrumentation, the CNL currently houses approximately 80 researchers all focused on the development of more sustainable chemistry and chemical processing. As a community we continue to work on the grand challenges associated with both ~~the~~ pharmaceuticals and fine chemicals, the CNL is already exceeding expectations, offering significant savings in terms of energy consumption and water use compared to more conventional laboratories. The intention is (i) to demonstrate that the unique environment in the CNL promotes new, innovative thinking in research on Sustainable Chemistry and enhances the quality of the scientific output and (ii) to provide an exemplar that can act as a blueprint for new, more sustainable chemical laboratory buildings for both academia and industry across the world. Its role has already been recognized by both regional and national architectural awards, particularly in the context of sustainability and functional design.

At the other end of the supply chain is the use of chemicals once they have been manufactured. Our contention is that, up till now, much of the focus of Green Chemistry has been on the toxicity of the chemicals [6] and the waste that is generated in their manufacture [5, 6] rather than the amount of chemical that is used in a particular application. This is exacerbated by the common business model for chemicals which generally aims to maximize the amount of chemical that is sold while ignoring the fact that most end-users of chemicals are more interested in the effect generated by those chemicals rather than the amount of the chemical that they actually consume. Thus patients take medicines to get well again, rusty cars are painted to prevent corrosion, surfaces are treated to repel water, etc.

Three years ago, we proposed a new metric, the F-Factor, the weight of chemical required to give a given effect, as a means of comparing the sustainability of different products [18]. We illustrated its application by applying it to amount plastic used in two similarly-sized water bottles and, particularly, the weight of plastic used in the caps of those bottles (in our example, one cap weighed nearly 5 times the weight of the other!). Plastic water bottles are quite a good example of where change may be possible at least in the UK, because public attitudes to the use of plastic in these bottles has been transformed over a period of literally only a few weeks by a TV programme showing the effect of plastic waste on the world's oceans.

Very recently, we have proposed a radical generalisation of the F-Factor, which we have called a "Moore's Law for Chemistry", MLFC [19]. Our proposal was inspired by Moore's Law which was formulated in the 1960s to rationalize the rapid rate of innovation in integrated circuitry [20, 21]. It proposed that the density of transistors in a given circuit would double every 18 months and the cost of their production would halve. Remarkably, it has held true for more than 40 years. We are now using hand-held devices with computing powers far exceeding that of huge main frame computers of the 1960s.

The MLFC proposes that chemists should strive to reduce the amount chemical needed to produce a given effect by a factor of two every five years. Thus, after 15 years, a given amount of chemical should be able to provide 8 times (e.g. 2^3) the effect and, therefore, to satisfy the needs of 8 times the number of people. Of course, achieving dramatic reductions might sometimes involve changing the particular chemical used to achieve a given effect but the general principle would hold, the needs of more people could be satisfied by using the same amount of chemicals.

The MFLC would require a change to many of the existing models for chemical manufacture but we note that there is already a move in the right direction with the concept of Chemical Leasing [22]. On the positive side, the MLFC fits the environmental zeitgeist by encouraging the reduced use of chemicals. More importantly, we believe that the MLFC is a vision that could be shared by all the stakeholders in the chemical enterprise including academics looking for new scientific challenges, manufactures seeking more effective and efficient processes, policymakers striving to satisfy the needs of growing populations, end-users wanting to have better products and members of the general public who feel passionately about the environment. Such a shared vision would be a strong driver not only for change but for change for the better.

This brings us back to the SDGs. Chemicals are central to achieving many of the SDGs including zero hunger, improved health and wellbeing, clean water and clean energy. So how could the MLFC impact on the SDGs? First, and most importantly, the MLFC could reduce demand for chemicals from currently developed countries so that existing manufacturing facilities can produce a surplus to address the needs of those in economically developing regions. Secondly, the MLFC will change the way that people think about chemicals and it will give everyone a shared vision of how our use of chemicals can become sustainable.

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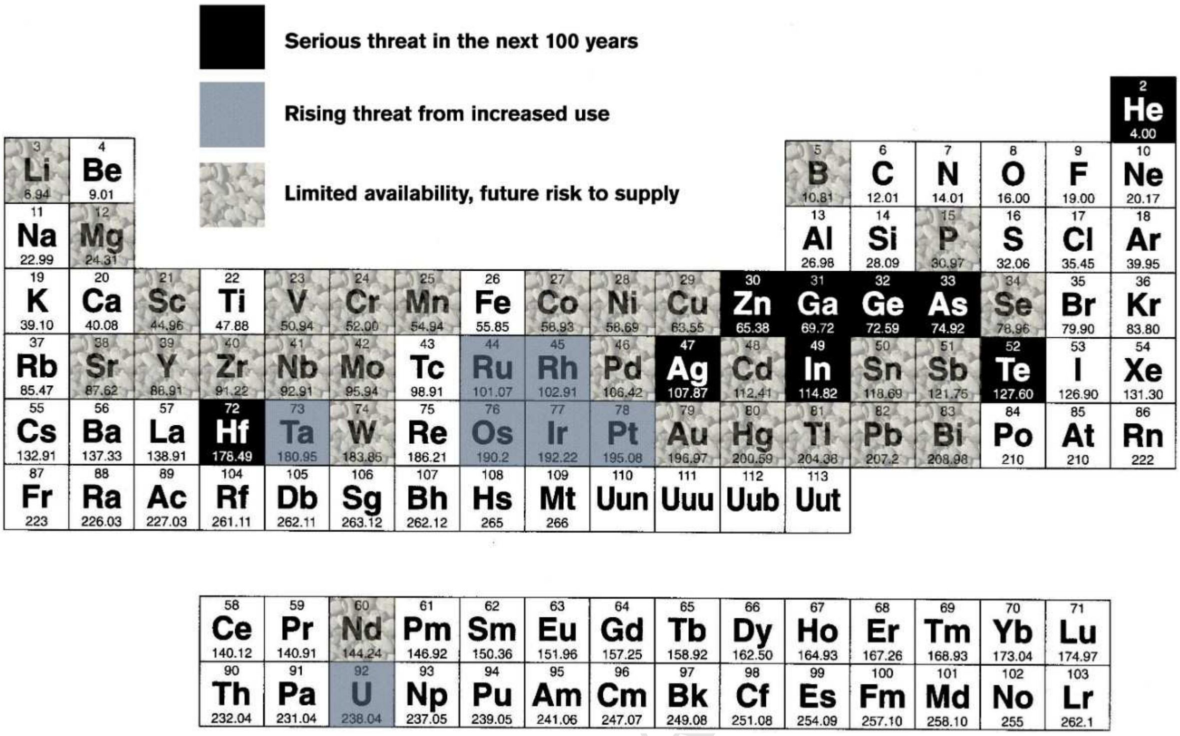

Figure 1: The Periodic Table of "Endangered Elements" ignoring radioactive elements apart from U. Adapted from Refs 13 and 14.

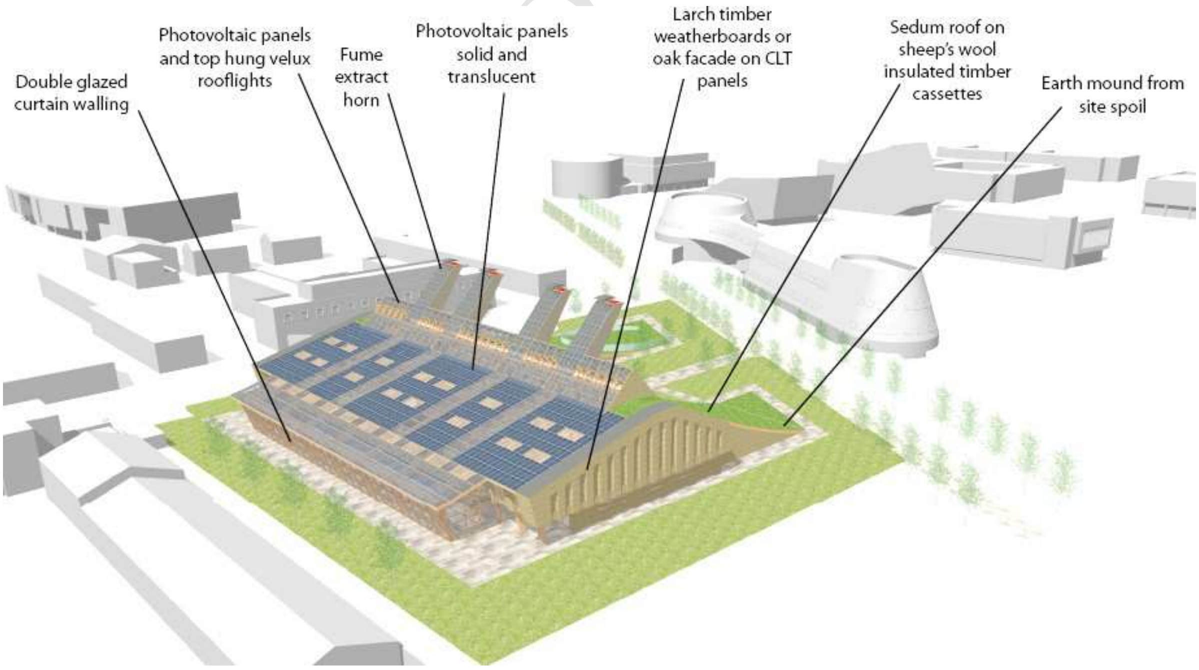

Figure 2: The design and important features of the GSK Carbon Neutral Laboratories. The building is constructed largely of sustainably sourced wood and the use of concrete has been minimized. The orientation and profile of the building is designed to harness the prevailing wind to assist extraction from the fume cupbards. For a virtual tour of the partly complete building see [17].