SUSTAINABILITY ON ENGINEERING PROGRAMMES; THE NEED FOR A HOLISTIC APPROACH

Edmond P. Byrne and John J. Fitzpatrick
Department of Process & Chemical Engineering, University College Cork, Ireland

***Abstract*-The teaching of sustainability on engineering curricula has increasingly become an essential feature. This has coincided with an increased focus on sustainability by professional institutions through stated policy positions and documents, though accreditation documentation has yet to be brought into line with these emerging positions.**

The creation of a sustainable society is a complex multi-disciplinary multi-stage project that will necessarily dominate mankind's endeavour throughout the coming century. The pathway to a road towards sustainability will require a paradigm shift among society in general. Sustainability is a normative endeavour with uncertain outcomes requiring collaboration, teamwork and an ability to work with, respect and learn from other disciplines and professions as well as local communities and governments. This is largely new territory for the engineer. Moreover this approach can only be embraced by the engineer who sees value in and a rationale for pursuing it. Engineers must clearly see the contribution they can make; they need to see how many of the fundamental or threshold concepts in engineering can be employed as central and basic tenets of the evolving meta-discipline that is sometimes called sustainability science. This can only really be achieved if sustainability exists as a common threadline throughout programmes, in such a way that it is conceived as a necessary lens through which all engineering practice is filtered.

Once this is achieved engineers will be well positioned to take the lead in moving towards developing a sustainable society rather than just designing the tools to move towards this goal as mere 'paid hands'. This paper will examine some existing basic threshold concepts in engineering and show how these can be used to embed sustainability throughout curricula so as to provide the graduate engineer of the twenty-first century with the motivation, vision and tools to be the leaders in our shared quest to create a truly sustainable global society.

I. A ROLE FOR ENGINEERS IN CREATING A SUSTAINABLE SOCIETY

A. An unsustainable global society

Human society faces an uncertain future. Continued unsustainable use of natural resources is leading to ever growing imbalances, placing us on *"a brutal collision course"* with our natural environment [1]. Nowhere are these imbalances more pronounced than through the increasing levels of atmospheric carbon dioxide and other greenhouse gases resulting from anthropogenic activity. These elevated levels are recognised as the principal driver behind a rate of climate change over and above the underlying background rate [2], and one which appears to be increasing and at an ever greater rate [3,4,5], and with more severe consequences [6] than previously considered. Not only have previous climate change estimates tended to err conservatively, there is also *'a significant risk that many of the trends will accelerate'* [7]. The problem with accelerating climate change (ACC) is that, like an accelerating vehicle, it is destined to eventually go out of control with devastating consequences, unless a brake is applied in timely fashion.

It is in this context that we must therefore, confront the *"harsh reality"* that *"not only are we exhausting and plundering the resources of the earth at unsustainable rates, but we are on the threshold of unimaginable devastation that climate change is likely to bring"* [8]. Confronting this reality will require a paradigm shift leading us to *"alter our economic and production systems and ways of living radically*", in short *"a new Enlightenment, to redefine our notion of progress"* [8]. Additionally, it has been suggested that this will require *"an educational framework that not only follows such radical changes, but can take the lead"* and this will involve *"fundamental changes in the creation, transmission and application of knowledge in all spheres and at all levels"* [8].

B. Economic parallels

Parallels can be drawn between the ongoing unsustainable use of the earth's resources and the current global recession. It was observed by many respected economists as far back as 2003 that the global economy and the US in particular was on an economically unsustainable pathway, which manifested itself most clearly in the property markets and associated growing levels of indebtedness [9,10]. Yet, while this analysis was generally accepted, most governments, businesses and individuals largely continued to operate as usual, riding on the strong economic growth rates that continued unabated for a number of years thereafter in the hope of ultimately achieving a 'soft landing'. Even when the downturn came, it was initially met with incredulity by many, including governments, who at first hoped to explain it away as a sub-prime correction centred on the USA, and then as a 'credit crunch' caused by a collapse in inter-bank confidence and lending. In boom times economists often tend to underestimate growth rates and when the economy hurtles into recession, a similar underestimation may also occur. By the time the tumble had taken hold, and governments and businesses had finally woken up to the fact that the world was indeed heading into a very significant recession, extreme and panicked governmental and international firefighting measures would prove too little and too late to ward off what appears to be a 'great recession' with all its consequences. Indeed some have suggested that in fact *"the global economy might be at some kind of tipping point"* [11].

We appear, in many respects, to be at around that 2003 moment in terms of global resource use; the pathway we are on is clearly and demonstrably unsustainable. This has resulted in the creation of an environmentally related bubble economy maintained by the fundamentally unsustainable nature of our global society [12]. The United Kingdom government's chief scientist has suggested that a *"perfect storm"* of food, energy and water shortages emanating from our unsustainable trajectory is likely by 2030 unless changes are made now [13]. Even if we try to turn things around, it will be extremely difficult at this point to engineer a soft landing towards a sustainable pathway, and human nature being what is it, it is easier for us, as with purely economic bubbles, to ignore the problem so long as things appear to be reasonably normal on a superficial level at least, unless and until there is a severe and rapid deterioration. We are often only jolted into action by severe paradigm shifting events, by which time the first response is often disorientation, squabbling and hopelessly inadequate firefighting measures. Should we not have achieved a sustainable society by the time the earth finally reaches climatic and ecological tipping points, any current economic woes will appear wholly insignificant by comparison to the effects (environmentally, economically and socially) of a changing climate which is allowed to accelerate out of control. This will be accompanied by severe weather events, widespread flooding, sea level rise, drought, food shortages and famine, habitat and species extinction, and a rapid depletion of vital natural resources, including water. In such a scenario, our most basic needs will be jeopardised as will the very survival of our society. That point is probably a lot closer than most of us would either envisage or wish, as scientific models, much like those of economists, have habitually tended to underestimate the rate of degradation of our natural environment [3,4].

If we are going to have any chance of putting the breaks on this unsustainable juggernaut therefore, we must first of all begin to appreciate the scale of the issue on a global and collective basis. Then we must work together to find a sustainable pathway and to do this we must have leaders who can chart a way forward. Engineers are well placed on all these fronts and therefore are potential and obvious key players.

C. A new engineering paradigm

Engineers, just like society at large must appreciate the magnitude and the immediacy of the task at hand if they are to be expected to help design a pathway through technological and social innovation, never mind provide leadership on this. A key outcome of having reached a point of realisation is to realign one's conceptualisation of the practice of engineering from something which might be characterised as 'design with constraints' (e.g. economic, environmental, safety, ethical) to one where sustainability (and all that this entails) becomes the very context of engineering practice, the lens through which all engineering practice is filtered. At a professional level, engineering institutions appear to have reached a point where the significance of achieving a sustainable society is being realised, at least according to their relevant documentation, policies and vision statements [14,15,16]. The Engineers Australia Sustainability Charter [15] is among the most progressive among these and states; *"sustainable development should be at the heart of mainstream policy and administration in all areas of human endeavour"* and this *"requires a fundamental change in the way that resources are used and in the way that social decisions are made"*.

Here an engineering institution is making statements that relate to society as a whole and thus by implication, recognises the normative and multi-disciplinary role that engineers can and must play in helping achieve a sustainable global society while also inviting its members to take a larger global view of their roles and perhaps take the lead in finding solutions to relevant issues.

Moreover, there have been a number of parallel initiatives aimed at promoting sustainability in engineering education, notably the 1997 Joint Conference on Engineering Education and Training for Sustainable Development in Paris [17] which called for sustainability to be *"integrated into engineering education, at all levels from foundation courses to ongoing projects and research"* and for engineering institutions to *"adopt accreditation policies that require the integration of sustainability in engineering teaching"*. Furthermore it noted that *"retraining all faculty members"* would be *"important in implementing the new approach"*. The 2004 Declaration of Barcelona [18] resulted from the second of a series of International Conferences on Engineering Education for Sustainable Development, hosted by the Engineering Education for Sustainable Development (EESD) Observatory, a group created by three European technical universities to the forefront of education for sustainable development; UPC Barcelona, Spain; TU Delft, The Netherlands and TU Chalmers, Sweden. This report focussed on the need for engineering education to incorporate many of the social aspects of sustainability into programmes in an integrated fashion and for engineers to *'apply a holistic and systemic approach to solving problems'*.

These initiatives have not yet been incorporated into the accreditation documentation of the professional institutions however. The 'engineering design with constraints' approach is still evident. For example ABET have eleven learning outcomes based requirements of graduates, including *"an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability"* [19].

Accreditation documentation from other professional engineering institutions provides for similar requirements. The result of this, along with the scepticism or ignorance of many engineering educators of the need for sustainability as a core tenet of engineering practice, as well as the fact that historically sustainability was not embedded into programmes, means that at best sustainability is often seen as yet another bolt-on topic, in addition to a long list of others (e.g. those listed by ABET above). Meanwhile, the 'engineer in the street', in part perhaps as a result of their own educational and professional training, is not as convinced as the professional institutions of the need for creating a sustainable society. Indicative of this viewpoint perhaps is the fact that a majority of respondents (54%) to an online IChemE survey [20] believe that sunspot activity overshadows any anthropogenic factors in causing climate change. Similarly Ref. [21] reported scepticism surrounding issues of sustainability among many respondents to an AIChE survey which looked at the major issues facing the profession over the next twenty five years.

In common with society in general, a large proportion of engineers it appears, do not seem to recognise the implications, socially, economically and environmentally, that the transfer to a sustainable pathway represents. A degree of convenient complacency prevails whereby less unsustainable systems, activities or processes are routinely labelled as being "sustainable". Such claims may be employed as marketing devices but they serve to lull society into a false and potentially perilous sense of security. Something that is less unsustainable than a previous incarnation is still nevertheless unsustainable, and merely slows the advance toward the aforementioned 'collision course', while failing to divert from it.

Claims by organisations that their operations are currently either sustainable or carbon neutral or close to achieving these therefore have to be treated with a degree of scepticism, particularly so long as the prevailing societal structures remain. What do these claims really mean? Are they just a slogan aimed at improving sales and making the organisation, shoppers, investors and/or employees feel better about themselves? Are such organisations claiming to be genuine oases of sustainability in an otherwise unsustainable society? Or do they really mean that they are (striving to be) less unsustainable than heretofore, which in itself of course is a worthy and well-meaning goal. For example, it is virtually impossible to envisage how any organisation can ship product manufactured by similar production processes as heretofore, from one side of the globe to the other, using the current conventional, mostly fossil fuelled methods of transport to large centralised stores, to which large numbers of people travel reasonably large distances in mainly fossil fuelled vehicles to shop, and still claim to be carbon neutral. So long as traditional manufacturing processes, supply chains and organisational structures remain in place for large organisations, by virtue of the way our global society is structured and fuelled, it is hardly conceivable that any single organisation, never mind society as a whole can claim to be either sustainable or carbon neutral, regardless of the amount of carbon offsetting that may be involved to enable such claims to be made. The globe simply isn't large enough to incorporate all the trees that would need to be planted if every company were to take this approach, and still accommodate the needs of several billion humans.

Organisations operate within the society that they inhabit, and you can't have sustainability in one without achieving it in the other. Therefore claims, such as that by the British retailer Marks & Spencer [22], that it is aiming to be carbon neutral by 2012 at best may send out a complacent message to customers i.e. that a sustainable future is just around the corner, and thus therefore does not require a paradigm shift in the way society operates: all it takes is for every other organisation to follow suit. Indeed the 62% of customers of this particular retailer who either 'can't see the point' or who feel a sustainable future is 'not their problem', would probably console themselves that by 2012 the issue of ACC, if it exists at all in their view, will soon become a thing of the past, particularly if they remain customers of this and other similar organisations. In reality however, some basic engineering analysis will show that so long as the current societal and technological model persists, a carbon neutral global society will remain an elusive goal.

D. Sustainability in engineering education

The EESD Observatory publish *"a biennial survey and ranking of European Universities of Technology that lead the way in integrating Engineering Education for Sustainable Development into their policies, curricula and in-house activities"* [23]. The ranking is based on five criteria, drawn from the Barcelona Declaration: university policy, number of sustainable development related courses and specializations at both undergraduate and postgraduate levels, the degree to which universities promote the embedding of sustainable development in curricula and the extent of adoption of an environmental management system in-house by universities. While the setting up of specialized programmes in sustainability, environmental and energy engineering is both a popular and useful endeavour it is the penultimate factor, in line with the recommendations of the aforementioned 1997 Joint Conference, which forms the focus of this paper.

Success in embedding sustainability into engineering curricula on a broad basis has in general been patchy. A number of universities have attempted to place sustainability at the core of their engineering curricula with varying degrees of success and engagement [24,25,26,27,28]. Just sixteen of the institutions included in the 2006 EESD Observatory survey scored over six on the ten point scale while none attained an 'inspiration score' of nine or better. Even for some pioneers in this area, the gravity of the situation appears at times almost too large and problematic to be taken seriously; for if it were, it would simply all-consume our daily lives. The following sentence appears on the promotional website for the masters chemical engineering programme specializing in sustainable development at Chalmers University of Technology, Gothenburg: *"Sustainability is today recognised to be essential for the survival of human society, and many new career opportunities are emerging in the field of sustainable development."*

It's as if it's just easier, as a coping, and perhaps marketing mechanism to focus on the good career paths that are available instead of the larger, and altogether graver picture. Of course this is not atypical of the human condition; we appear to have an inherent inability to be overly concerned about anything that is on a timescale of more than a few years; perhaps this is an inherent coping mechanism designed to prevent us from becoming all-consumed by our inevitable deaths. At any rate, it means that the longitudinal and inter-generational aspects of sustainability present difficulties for us.

II. Embedding Sustainability Through Key Engineering Threshold Concepts

A. The need to embed sustainability

Engineers must comprehend the unsustainable trajectory of the existing societal model if sustainability is to become the context through which engineering is practiced. Only then can they even begin to appreciate the central role that they as engineers can and must play in developing a sustainable society and to appreciate the multi-disciplinary nature of the task. In essence, engineers must realise how sustainability is to engineering what the sun is to life, while of course there are additional critical factors required to sustain life. This fundamental perspective cannot however be assumed as given among incoming or existing engineers. Embedding sustainability throughout engineering programmes can best promote this mindset among graduate engineers however.

Embedding sustainability requires more than just the inclusion of sustainable technologies, tools and processes in engineering programmes. While dedicated modules and elective streams can serve a useful purpose in adding depth to programmes, they alone cannot effectively demonstrate how sustainability should be the context through which twenty first century engineering must be practiced if the programmes themselves do not inherently and consistently demonstrate the need for sustainable practice. Instead, extra modules or electives simply bolted on to an existing curriculum, without the concept being rooted throughout the programme, are more likely to be perceived as yet another constraint on an already overburdened programme.

B. Threshold concepts in engineering education

A number of the fundamental tenets or 'threshold concepts' [29] related to engineering are ideally suited to helping realise a sustainability informed paradigm. These concepts include material and energy balances (fundamental to all chemical engineering curricula), the systems approach that these concepts incorporate, the second law of thermodynamics and the associated concept of entropy. Armed with these tools, particularly when presented in a global context, the engineer can build up an effective and straightforward conceptual model of the world which can be employed to determine how (un)sustainable a given activity may be. Informed by this model, the engineer can also become a productive partner in the collaborative quest for a sustainable society with other professions, disciplines, politicians and communities. They can play an active part in the emerging meta-discipline sometimes referred to as sustainability science, and can even lead this endeavour. The remainder of this paper will involve examining some of the aforementioned threshold concepts, along with some examples of their application.

C. Material and energy balances

The laws of conservation of matter and energy are among the most fundamental laws of science. Engineers apply these through applying material and energy balances around given defined systems to determine material and energy flowrates throughout particular units, processes or systems. In equation form, they can be represented by (1):

Material (or Energy) In to a System
–Material (or Energy) Out of a System
+Material (or Energy) Generated within a System
– Material (or Energy) Consumed within a System
=Accumulation of Material (or Energy) in a System (1)

Material and energy balances are core threshold concepts for chemical engineers. They are employed, for example, to compute material and energy flowrate through a manufacturing or production process at the initial design stages to enable the construction of process flow diagrams and estimate utility requirements and hence to proceed to more detailed engineering design. They are applied by enclosing that arbitrary part of the universe that is of interest, the system, with a system boundary line. Flows in to and out of this system can then be calculated based on solving a series of simultaneous equations for each of the relevant entities as well as overall material or energy flows. These constraints are typically applied by the engineer up to the process or plant scale, for example in characterising material and/or energy flows in a process plant, combustion engine, air conditioned building or dialysis unit. They are however inherently capable of being applied at any scale, including global, and can therefore provide an overview of the respective material and energy flows throughout society. They can hence provide a straightforward model of the nature and degree of unsustainability for a given system, since as Ref. [1] puts it *"human sustainability is possible only when it follows natural laws of mass and energy balance"*. Because material and energy balances are generally covered in the first year of a (chemical) engineering degree, typically as part of an introductory module, they are an ideal vehicle for introducing the concept of sustainability to engineers and embedding sustainability in the curriculum from an early stage. They can then be revisited later on in the programme in an applied manner in the form of life cycle analysis assessment, which is based on these fundamental concepts. This can be included perhaps as a part of a dedicated sustainable development or environmental engineering module. Moreover they can form the basis of a systems engineering approach throughout programmes [30], which can manifest itself most appropriately in the final year design project.

Material and energy balances are however not widely understood or applied among disciplines outside of engineering. A systems approach where a material balance is constructed on a global scale can help examine commonly held view of neoclassical environmental economists for example, that *"sustainability does not require restrictions on material consumption"* [31].

In teaching material and energy balances, the scale can therefore be extended from process to global to incorporate a sustainability informed paradigm. Material and energy flows can be set up within the respective systems and across the system boundaries and material and energy balances can be set up in order to quantify the respective amounts for each of the flows. Students can quickly see the bigger picture in this manner, and can easily grasp the rationale behind striving for a sustainable world. A useful case study here might be the case of Easter Island, where it has been hypothesised that the many incomplete giant statues on this small south Pacific island were the result of a rapid collapse in the island's society after its resources (including its trees) were exhausted in a construction boom around the 17th century [32]. The treeless island could not even enable the starving islanders build boats to evacuate across the sea and thus the island's society and population suffered a rapid and massive decline into long term subsistence living and poverty.

Students might be asked to reflect on the implications of the Easter Island experience with the world today and the roles and responsibilities of engineers in preventing similar catastrophic events. This can help them see the need for sustainable design and they can be invited to apply this rationale when designing processes at a relevant scale. They might consider if sustainable processes can be created by incremental improvements in process and/or energy efficiency or do the processes need to be fundamentally redesigned? How might this be done? Similarly, on the materials side, the requirement for sustainability in terms of materials is brought into focus. Engaging in this process facilitates shifting the paradigm; demolishing established preconceptions and creating new understandings.

Figure 1 demonstrates a model of the biosphere, which is taken here in a broad sense to incorporate the sphere of influence of human activity. A system boundary is drawn around that which incorporates human activity with a broken line. Natural resources and the atmosphere - our natural environment are positioned outside the system boundary. These are resources that through our prevailing social model we would have heretofore recognised as being 'free' i.e. free to exploit, for the benefit of mankind and society. However, while this construct may have been realistic for all our evolutionary history, whereby we could allow flows of water and carbon dioxide without limit with negligible environmental or societal

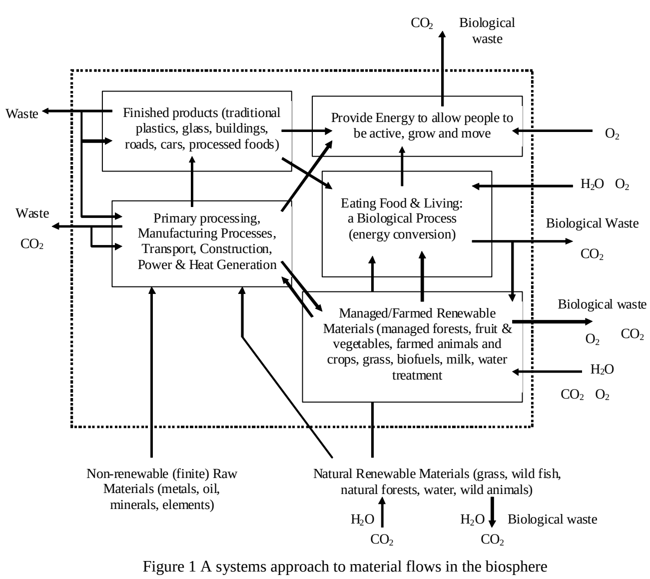

Figure 1 A systems approach to material flows in the biosphere

consequence, our society has in the past couple of centuries outgrown this mode of operation and the sheer scale of the respective material inputs and outputs across this system boundary are now so great that that which is without the system boundary (our environment) is in grave danger of collapsing, thus bringing down that which is within (human society). Only a radical alteration in the magnitude of respective flows with drastic reductions across the system boundary can prevent such collapse from becoming a reality. Of course, human society cannot be a closed system with respect to its environment, rather a symbiotic relationship must be established where flows are by and large balanced.

Of course Figure 1 can be redrawn to accommodate corresponding energy flows within society. While processes and systems can be radically redesigned to create material equilibrium between society and its environment, the same cannot be achieved for energy. While the global system that is the biosphere (i.e. all the contents of Figure 1, both within and without the system boundary) can indeed be defined as a (materially) closed system (ignoring the odd meteorite, satellite and space shuttle), the same cannot be said for energy. For life to exist, a constant source of energy is required to enter this system as ordained by the second law of thermodynamics (see later). Thankfully a plentiful source exists in the form of our nearest sun, which can be classified to all intents and purposes as a longitudinally infinite energy source. While the vast majority of all our energy needs comes either directly or indirectly from the sun (excepting nuclear and geothermal for example), the long term problem with many of these is that they either create material imbalances across the system boundary through depletion of finite resources, creation of hazardous wastes and/or the addition of carbon dioxide. Over time, these can have very significant derivative effects; the build up of CO_2 in the atmosphere for example, is recognised as a major contributor to ACC and all that this implies.

Given the gigantic power input we receive from the sun, it is theoretically possible to take all our energy needs from this source alone, even by just harnessing all the solar energy falling on a very small fraction of the world. Additionally there are other renewable energy sources which do not create unsustainable material or energy imbalances (Figure 2). Why then are these sources not being employed on a very large scale? Clearly, for this to happen we need a societal, economic and technological revolution. The technological aspect is in many ways the easy part; many of the required technologies either already exist or can readily be developed. Is it the place of engineers to wait around until society signs the cheque to design and develop these technologies and systems? Or, do engineering educators have a role and a responsibility to help graduate engineers see the bigger picture and thereby

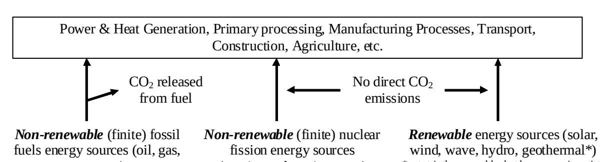

Figure 2 Sources of energy driving human activity

envisage a responsibility for engineers in informing and leading the required social, economic and technological revolution to meet the requirements and expectations of society in a new and sustainable manner?

D. A systems approach to process and product design

Most engineering programmes have a final year capstone course which involves group design. Mechanical and electronic engineers typically design physical artefacts involving mechanical and/or electronic features. A principal learning outcome here is to integrate a number of the key threshold concepts associated with the discipline which have been covered throughout the students programme in a practical and applied manner. For the chemical engineer, the traditional project involves designing a process to produce a given product; a bulk chemical, a pharmaceutical or a food product for example. Bulk chemicals have traditionally been the most common, and as part of the design the group would consider alternative possible processes to produce this product and then choose a suitable process having analysed and compared the available processes subject to a number of constraints, including economic, environmental, safety, availability, and so on.

A similar exercise is also often undertaken in modules on process design or indeed on sustainability, environmental or green engineering. An example of this is the production of the vinyl chlorine monomer, the precursor to the PVC polymer [33]. Here two process options are investigated; one with an ethylene raw material, the other using acetylene, and a number of novel unit operations are shown to lead to a volatile organic compound (VOC) emissions reduction in one process compared to the other. The system can then be extended to incorporate raw materials and PVC production and a life cycle analysis can be undertaken. Ref. 24 provide a similar example. While these are interesting and in some ways innovative studies, they remain firmly within the constraint ridden paradigm of traditional chemical engineering practice. As a result of this the student is only challenged to compare one unsustainable system with another less unsustainable system.

The appropriate question from a sustainability standpoint is not simply: What is the best way to produce vinyl chloride? but: Does this entity really need to be produced? Questions such as: What do we do with vinyl chloride? and: Are there other materials that can take its place, that are even less unsustainable or ideally, sustainable? Could for example, lactic acid, and the resultant biodegradable plastic polymeric lactic acid (PLA) take the place of PVC for many applications? Would this be a more sustainable process? In general, how feasible is it to produce plastics from renewable materials as opposed to oil? What are the technical and economic barriers preventing for example, the production of biodegradable polymeric materials from CO_2 and epoxides from non petroleum derived sources such as limonene, an oil abundant in orange peel [34] or from thermoprocessible plastics produced by simple modifications of oxygenated biomaterials? [35]. These are the questions that will arise if a much broader scope is envisaged. Questions too that will ignite the interest of curious undergraduate engineers and which can engender a sense of empowerment and responsibility to search for genuine alternative, sustainable design options throughout their future careers. Again assignments such as this can enable engineers to envisage a wider, more normative role for themselves where they can influence key production decisions and directions. This a not a mere hypothetical situation; the chief executive of the Irish peat based fuel company Bord na Móna, a chemical engineer, realised a couple of decades ago that this was not the fuel of the future, and so left this organisation to found a successful international wind energy company, Airtricity [36]. Plastics companies who hire engineers who see their role as merely "paid hands" to produce plastics more efficiently may find themselves without a market over time.

Such a broader sustainability informed approach will engender a greater level of excitement and possibility among engineering students and graduates. It can also promote an investigative research and entrepreneurial spirit where innovation flourishes as engineers seek out new sustainability based designs. The range and breadth of applications are almost endless; from the potential use of microreactors and new generation separation unit operations based on highly selective nanomaterials to applications involving the exploitation of biomimicry [37, 38].

E. Entropy and the second law of thermodynamics

The second law of thermodynamics is one of the most elegant and profound laws of the universe we inhabit. We value energy because the biosphere requires a constant supply of it, but only as a means to produce it in high quality or concentrated form, that is, with low entropy (Figure 3).

The first law of thermodynamics tells us that energy cannot either be created nor destroyed. Therefore energy in itself has little value, unless it is a concentrated form. This is where the second law comes in. It tells us that the entropy of the universe increases with any spontaneous process, and as this process proceeds we can practically benefit from it by directing a certain amount of the diffusing energy towards useful work (Figure 4). Accordingly we value low entropy items with structure such as buildings, fuel sources, foods, gadgets, and so on, though the second law tells us that these naturally will fall into decline over time, once provided with sufficient activation energy.

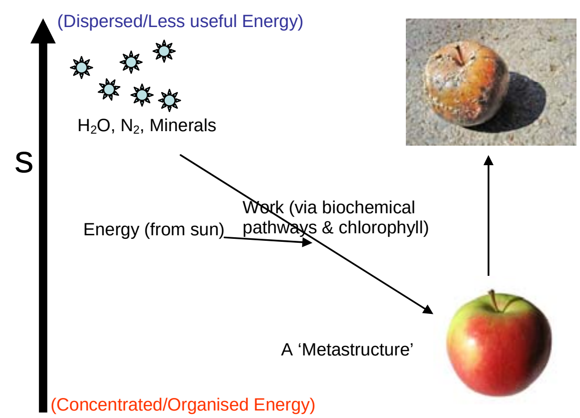

Figure 3 Entropy changes associated with a growing and rotting apple

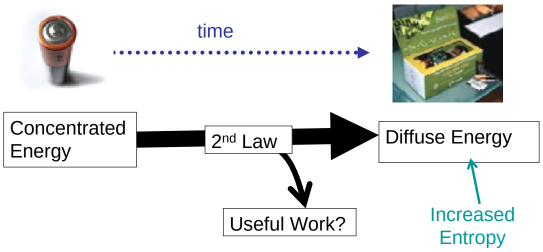

Figure 4 Second law of thermodynamics

On the other hand the direction of this process can be reversed if energy is applied to produce a low entropy outcome. The biosphere can be seen as an interrelated series of second law cycles where organisms give up their low entropy energy which can be used to feed other organisms to allow the latter store energy and reduce entropy. The thermodynamics class can thus help provide students with a fuller appreciation into the nature of energy, global energy flows and the associated key parameter of entropy. If the entropy of the universe is increasing does that mean that the universe itself is inherently unsustainable? Where does that leave us? What about timeframes? The inherent links between energy, entropy and sustainability [39] consequently becomes clearer to the student as does the rationale behind suggesting that the rate of entropy change combined with the flow of energy throughout the biosphere may provide a reasonable basis for measuring the degree of (un)sustainability of given processes [40], or the assertion that there is *"minimum entropy production in sustainable systems"* [41]. The broader context having been established, the focus can then be switched to the process scale as appropriate.

F. Engineering ethics

Engineering ethics education has traditionally typically focused on case studies where possible courses of action of the individual are examined. This approach has been characterised as being rather artificial, in that it tends to oversimplify issues by presenting well defined problems that often neglect the social complexities of real engineering practice [42]. This Ref. [42] argues constrains the engineering student and expects a minimalist approach, instead of appealing to their instinctive desires to do good, *"to better the environment, conserve energy, bring appropriate technology to developing countries"*.

Ref. [42] suggests that the whole engineering programme should be reformed; *"to enable student (and faculty) understanding of the social as well as instrumental challenges of contemporary professional practice and what this might mean for the profession's 'social responsibility' (and ethical behaviour of the practicing engineer)."* This view is supported by Ref. [43] who in addition notes gaps in engineers' conceptualisation of sustainability, particularly the social element and reflects; *"Engineers need to consider how they intervene in the public policy arena and whether these interventions enable or constrain the move towards a sustainable and just world."*

A greater focus on the issues of sustainability and all that this entails in the ethics class, along with appropriate case studies would provide opportunities for deeper reflection of the roles and responsibilities of engineers. This will help students understand the need for a multi-disciplinary approach involving social and political engagement in solving multi-faceted and messy sustainability related problems. Such an approach can provide engineers with a greater sense of self-awareness and motivation than a series of well defined formulaic and individualistic case studies on engineering ethics.

III. Conclusions

Engineers have designed the physical environment throughout the society in which we live. While the current societal model has to date served us well and has facilitated many significant advances over the past couple of centuries of our existence, it is premised on a model which is inherently unsustainable and therefore threatens society itself through significant deterioration of the earth's ecosystem. The most immediate manifestation of this is accelerating climate change resulting from elevated levels of greenhouse gases in the atmosphere. Widespread water and food shortages, severe weather events, flooding, drought and sea-level rise are all inter-related consequences of this failed model. We have essentially outgrown our planet on the basis of our imbalanced and unsustainable society. We must create a new society model based on a sustainability informed paradigm. To do this, all engineering practice must be filtered through a sustainability informed lens. As key players in redesigning society, engineers must recognise their wider responsibilities in this regard. While many professional engineering institutions appear to have recognised this and have expressed a desire for its members to work towards a sustainable society, they have not yet expressed this goal explicitly in their accreditation documentation. Nevertheless the urgency of the issue dictates that engineering education has an obligation to prepare graduates through programmes which embed sustainability. This global project requires a multi-faceted and multi-disciplinary approach. Green engineering, sustainability and/or environmental engineering modules or streams are useful in themselves but in order for this new paradigm in engineering practice to be realised, and for the engineering professionals to fully appreciate the concept and the pressing need for finding a road towards a sustainable society, a sustainability informed paradigm must be embedded throughout all engineering programmes. This can be facilitated by demonstrating the usefulness of a number of engineering threshold concepts in developing a sustainable society; material and energy balances and the second law of thermodynamics for example. The key issue is that sustainability should be a common threadline running throughout the engineering programme. For example, on capstone design projects the first key design objective should relate to realising a sustainable design option. Once a curriculum which emphasises sustainability as the context through which all engineering practice must take place is in situ, engineering graduates will be better equipped to comprehend the very significant challenges ahead, to work with other disciplines and stakeholders in addressing these challenges and indeed take the lead in our most important endeavour yet.

References

[1] T. Pereira, "Sustainability: An Integral Engineering Design Approach," *Renew. Sus. Energy Rev.*, 13, pp1133-1137, 2009.

[2] Intergovernmental Panel on Climate Change (IPCC), *Fourth Assessment Report: Climate Change 2007*. Geneva, 2007. Url: http://www.ipcc.ch/ipccreports/assessments-reports.htm

[3] L.K. Bogataj, *IPCC Fourth Assessment Report - Climate Change is Real and Here!* Pre-COP IPCC workshop. Warsaw. 2 October 2008. Url: http://www.ipcc.ch/graphics/presentations.htm

[4] S. Rahmstorf, "Sea Level Rise," *The International Scientific Congress on Climate Change, Global Risks, Challenges and Decisions.* Copenhagen. 10-12 March 2009. Url: http://climatecongress.ku.dk/

[5] N. Stern, *The International Scientific Congress on Climate Change, Global Risks, Challenges and Decisions.* Copenhagen. 10-12 March 2009. Url: http://climatecongress.ku.dk/

[6] J.B. Smith et al., "Assessing Dangerous Climate Change through an Update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern"," *PNAS*, published online before print February 26, 2009. Url: http://www.pnas.org/content/early/2009/02/25/0812355106

[7] Anon, "Key Messages from the Congress," *The International Scientific Congress on Climate Change, Global Risks, Challenges and Decisions*, Copenhagen. 10-12 March 2009. Url: http://climatecongress.ku.dk/newsroom/congress_key_messages/

[8] *4th International Conference on Environmental Education*, Ahmedabad. 24-28 November 2007. Url: http://www.tbilisiplus30.org/Final%20Recommendations.pdf

[9] P. Woodall, "House of Cards," *Economist*, 367, 8326, s3-5, 2003.

[10] Anon, "A Home-Grown Problem," *Economist*, 376, 8443, 69, 2005.

[11] Bank for International Settlements, *Bank for International Settlements 78th Annual Report.* Basel, 2008. Url: http://www.bis.org/publ/arpdf/ar2008e.pdf

[12] L.R. Brown, *Plan B: Rescuing a planet under stress and a civilization in trouble.* New York: W W Norton & Co., 2003.

[13] J. Beddington, "The Interrelated Issues of Climate Change and Food Security," *GovNet Communications' Sustainable Development 09.* London. 19 March 2009.

[14] Melbourne Communiqué. Melbourne, 2001. Url : http://www.icheme.org/sustainability/Melbourne_communique.pdf

[15] Engineers Australia, *Engineers Australia Sustainability Charter.* Canberra: Engineers Australia, 2007.

[16] Institution of Chemical Engineers, *A Roadmap for 21st Century Chemical Engineering.* Rugby: IChemE, 2007.

[17] Joint Conference Report, "Engineering Education and Training for Sustainable Development," *Joint UNEP, WFEO, WBCSD, ENPC Conference.* Paris. 24-26 September, 1997.

[18] Declaration of Barcelona, *2nd International Conference on Engineering Education for Sustainable Development.* Barcelona, 2004. Url: https://www.upc.edu/eesd-observatory/who/declaration-of-barcelona/declaration-of-barcelona/html2pdf

[19] ABET, *Engineering Programs Effective for Evaluations during the 2008-2009 Accreditation Cycle.* Baltimore, Maryland: ABET, 2007.

[20] Anon, "Do you think Global Warming is related to Cyclical Sunspot Activity and not CO_2 Pollution?," *The Chemical Engineer*, p.54, May 2007.

[21] J. Ziemlewski, "Where do you think we are headed?," *Chem. Eng. Prog.* 104, 11, pp43-50, 2008.

[22] Marks & Spencer, "Your M&S How we do Business Report 2008," London: Marks & Spencer, 2008. Url: http://annualreport.marksandspencer.com/pdf/m&s_how_we_do_business_2008.pdf

[23] Engineering Education for Sustainable Development (EESD) Observatory, *Status of Engineering Education for Sustainable Development in European Higher Education*, Barcelona, 2006. Url: https://www.upc.edu/eesd-observatory/why/reports/EESD%20Observatory2006%20Report.pdf

[24] F. Gutierrez-Martin and S.H. Hüttenhain, "Environmental Education: New Paradigms and Engineering Syllabus," *J. Clean. Prod.* 11, pp.247–251, 2003.

[25] R.A. Fenner, C.M. Ainger, H.J. Cruickshank and P.M. Guthrie, "Embedding Sustainable Development at Cambridge University Engineering Department," *Int. J. Sus. High. Ed.* 6, 3, pp.229-241, 2005.

[26] V.G., Gomes et al., "Chemical Engineering Curriculum Renewal," *Trans IChemE, Part D. Ed. Chem. Eng.* 1, pp.116-125, 2006.

[27] E. Favre, V. Falk, C. Roizard and E. Schaer, "Trends in Chemical Engineering Education: Process, Product and Sustainable Chemical Engineering Challenges," *Trans IChemE, Part D. Ed. Chem. Eng.* 3, pp.22-27, 2008.

[28] Holmberg, J., Svanström, M., Peet, D. -J., Mulder, K., Ferrer-Balas, D. and Segalàs, J. "Embedding Sustainability in Higher Education through Interaction with Lecturers: Case Studies from three European Technical Universities," *Eur. J. Eng. Ed.* 33, 3, pp.271-282.

[29] J.H.F. Meyer and R. Land, "Threshold Concepts and Troublesome Knowledge (1): Linkages to ways of Thinking and Practising." in *Improving student learning - ten years on*, C. Rust, Ed. Oxford, 2003.

[30] C. Elliott, and P. Deasley, *Creating Systems that Work: Principles of Engineering Systems for the 21st Century*, RAE, London, 2007. Url: http://www.raeng.org.uk/education/vps/pdf/RAE_Systems_Report.pdf

[31] L. Illge, and R. Schwarze, "A Matter of Opinion – How Ecological and Neoclassical Environmental Economists and think about Sustainability and Economics," *Ecol. Econ.* 68, pp.594-604, 2009.

[32] J. Diamond, *Collapse: How Societies Choose to Fail or Succeed.* New York: Viking Press, 2005.

[33] H.T. Bi, "Integrating Sustainability into Chemical and Biochemical Engineering Curricula at UBC," *AIChE Ann. Meeting,* Cincinnati, Ohio, November 2005.

[34] C.M. Byrne, S.D. Allen, E.B. Lobkovsky and G.W. Coates, "Alternating Copolymerization of Limonene Oxide and Carbon Dioxide," *J. Amer. Chem. Soc.* 126, 37, pp.11404-11405, 2004.

[35] V.H. Grassian et al, "Viewpoint: Chemistry for a Sustainable Future," *Env. Sci. Tech.* 41, 14, pp.4840-4846.

[36] E. O'Connor, "The Future is Offshore: An Interview with Dr Eddie O'Connor, CEO, Airtricity," *Refocus.* 7, 3, pp.62-63, 2006.

[37] J.M. Benyus, *Biomimicry: Innovation Inspired by Nature,* New York: HarperCollins, 2002.

[38] J. Benyus, and G. Pauli, *Nature's 100 Best: World-Changing Innovations Inspired by Nature.* White River Junction, Vermont: Chelsea Green Publishing Company, 2009.

[39] W. Norde, "Energy and entropy: a thermodynamic approach to sustainability," The Environmentalist. 17, pp.57-62, 2006.

[40] S. W. Hermanowicz, "Entropy and Energy: Toward a Definition of Physical Sustainability," *Water Resources Center Archives Working Papers,* University of California Multi-Campus Research Unit, 2005. Url: http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1048&context=wrca

[41] M-W. Ho and R. Ulanowicz, "Sustainable Systems as Organisms?," *BioSystems.* 82, 39–51, 2005.

[42] L.L. Bucciarelli, "Ethics and Engineering Education," *Eur. J. Eng. Ed.* 33, 2, pp.141-149, 2008.

[43] E. Conlon, "The New Engineer: between Employability and Social Responsibility," *Eur. J. Eng. Ed.* 33, 2, pp.151-159, 2008.