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CHEMICAL ENGINEERING IN AN UNSUSTAINABLE WORLD; OBLIGATIONS AND OPPORTUNITIES

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Abstract: Human society faces a set of unprecedented challenges emanating from the unsustainable nature of the current societal model. The creation of a new sustainable societal construct is required, essentially adopting a needs based approach over one based on ever increasing consumption. Failure to achieve this will result in the widespread destruction of our increasingly stressed environment followed quickly by inevitable collapse of society as we know it, both socially and economically.

Technology alone is insufficient to meet the challenges at hand; ecological, social and economic considerations must be incorporated through a multi-faceted and multi-disciplinary approach. Because chemical engineers possess a core set of threshold concepts which are central to a sustainable society, and because engineers will ultimately help design any new society, they bear a moral and ethical responsibility to play an active and indeed central role in its development. A new engineering paradigm is required therefore, whereby sustainability becomes the *context* of engineering practice. To achieve this, a sustainability informed ethos must prevail throughout engineering curricula. Both professional institutions and educators bear responsibility in ensuring this happens without delay. Some key threshold concepts are presented here to demonstrate how this can be advanced through the chemical engineering curriculum.

Keywords: sustainability, curriculum, professional ethics, society, environment, threshold concepts.

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AN UNSUSTAINABILE SOCIETAL MODEL

1.1 Stark challenges

Human society faces an uncertain future. By our continued failure to realize a sustainable society, we are neglecting *"our moral responsibility to protect the natural environment to such an extent that the survival and well being of future generations are not jeopardised"* (Perdan, 2004). Ever growing imbalances emanating from continued unsustainable flows of materials and energy have placed us on *"a brutal collision course"* with our natural environment while *"the consumption driven modern way-of-life continues un-abated in all fronts, everywhere"* (Pereira, 2009). Meanwhile these effects are exacerbated by a still rising global population. This set of circumstances are perhaps the inevitable consequence of our innate evolutionary compulsion to seek to exploit as much (wealth, material, energy) as we possibly can, since the rules of the evolutionary game demand that players routinely seek to strive for and value excess ahead of sufficiency. We are, in this respect victims of our extraordinary evolutionary success, a success which has positioned us as prime among species and resulted in us inhabiting almost every corner of the earth and venturing beyond. Accordingly no species has managed to manipulate their environment to anywhere near the extent that we have. This exploitative trait has resulted in an expansionary societal model which is no longer sustainable in a finite world whose limits have been reached (Figure 1). The dominant social paradigm dictates that we organise society in a way which envisages our natural environment as something that is to be exploited for our own isolated (short to medium term) ends (Dewberry and de Barros, 2009), thereby viewing our role as that of non participatory audience. We are of course, fellow actors with our fellow species within a shared natural environment, albeit capable of playing a predominant role. The current societal construct is longstanding and has historically been reinforced by several cultural and religious paradigms, for example the Judea-Christian tradition, whereby mankind's self perceived role is one of external domination; *"Be fruitful then and multiply, teem over the earth and subdue it."* (Genesis, 9:7). By this construct, nature exists to be exploited for mankind's exclusive interests, to the extent that failure to do so is to abdicate one's responsibility. While other beliefs have also existed within this and other traditions, this worldview was nevertheless fundamental in constructing a philosophical underpinning for both the Scientific and Industrial Revolutions; *"It is possible to reach a kind of knowledge which will be of the utmost use to men ..and thereby make ourselves the lords and possessors of nature"* (Descartes, 1638). Such an outlook has manifested itself in engineering practice and self perception through time; in 1828 Thomas Tredgold defined engineering as *“the art of directing the great sources of power in nature for the use and convenience of man”* while the forerunner to ABET, the Engineers' Council for Professional Development (EPCD), defined it a century and a half later in 1979 as *“the profession in which a knowledge of the mathematical and natural sciences gained by study, experience and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind”* (CETS, 1986).

For most of human existence however, such conceptions were an irrelevancy, since an unsustainable societal model could expand and flourish (economically) in a finite globe so long as resource limits were not yet met. The Enlightenment and the subsequent Scientific and Industrial Revolutions have however enabled mankind to reach and surpass these limits via a society marked by expansionary and resource profligate ambitions. That which has brought us our incredible success appears to be advancing our downfall.

The consequences of continuing along the unsustainable pathway that we have forged have been well documented. The collapse of the very environment which both envelops and permeates all human society will be followed by the inevitable collapse of human society itself; both socially and economically (Figure 1). On our current trajectory, to put it bluntly; *“the world as we know it is coming to an end”* (Taylor & Taylor, 2005). In practical terms, this means that globally, even basic societal needs will come under severe pressure, and soon. The British government’s chief scientific advisor has highlighted a series of devastating conditions, each imminent, which may come together concurrently sometime around 2030, thus setting the scene for a “perfect storm” (Beddington, 2009). These include the four elements of increased demand for energy, food and water as well as the effects of climate change. Each of the above issues are the inter-related consequences of our continued unsustainable societal pathway. As a case in point, the US Secretary of Energy and Nobel laureate Stephen Chu has suggested not only does he envisage *“a scenario where there's no more agriculture in California"* but that he can’t *“actually see how they can keep their cities going"* (Tankersley, 2009).

A significant manifestation of our unsustainable societal construct is the phenomenon of climate change at a rate over and above the underlying background rate. This is principally as a result of increases in atmospheric carbon dioxide and other greenhouse gases that have continued to build up over the past several decades due to anthropogenic activity (IPCC, 2007). The rate of climate change appears to be at greater pace than has been previously recognised (Bagotaj, 2008; CCSP, 2008; Rahmstorf, 2009; Stern, 2009), and with more severe consequences (Smith et al., 2009). Additionally, not only have previous climate change estimates tended to err conservatively, it has also been claimed that there is *"a significant risk that many of the trends will accelerate"* (Copenhagen, 2009).

Of course, we have already begun to experience the direct effects of a rapidly changing climate through widely reported effects such as habitat and species extinction and migration, extreme weather events, altered precipitation patterns (prolonged drought, torrential downpours and severe flooding), displacement of people, changing land use patterns, receding glaciers and ice caps and rising sea level. The massive ecological, social and economic cost to the Murray basin area of south eastern Australia for example, is already clearly evident in the wake of several years of sustained drought, resulting in very substantial loss of wetlands, agriculture and threat to population centres such as Adelaide (Draper, 2009). Similar problems arise in river basins in the Middle-East, Central Asia and in Southwest USA (Molle et al., 2009). 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 a timely fashion. Indeed, some would suggest that such collision is already inevitable on the basis that we have already surpassed an ecological tipping point (Lovelock, 2009). Such an assessment cannot of course be proven until it is too late, nor can it be used as an argument for not striving to construct a sustainable society.

Confronting the reality of our unsustainable pathway will therefore require a universal paradigm shift (Anderson, 2001; Segalàs et al., 2008) towards a sustainability informed worldview. Such a model would incorporate the three spheres of ecological, social and economic where the well being and survival of each is a dependent subset of the previous (as represented by the environment, society and the economy respectively in Figure 1).

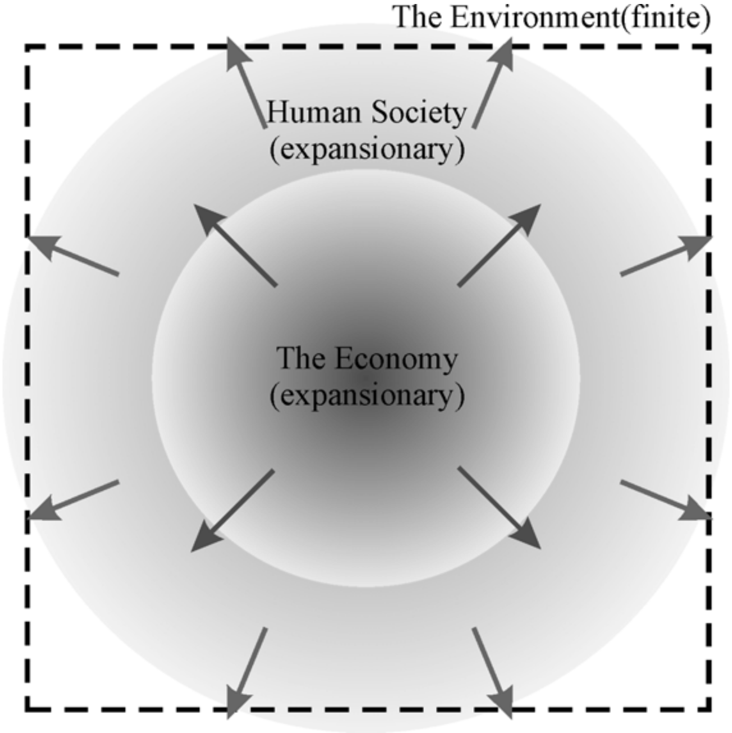

Figure 1 The three sphere model of environmental, societal and economic domains

The nature of this balance is problematic however, as it is a contested function of respective conceptions of sustainability. In this context a bottom line conceptualization may be appropriate, which recognises that *"absolute limits of these trade-offs are dictated by the need to maintain a functioning life-support system"* (Fischer et al., 2007). This may require *"a new Enlightenment, to redefine our notion of progress"*, whereby we must collectively *"alter our economic and production systems and ways of living radically*" (ICEE, 2007). This might be practically achieved through a deliberative political process with appropriate system regulation, essentially an overarching fourth sphere operating above the aforementioned three spheres which is designed to maintain an appropriate equilibrium between each (O'Connor, 2006). Given the finite nature of the planet and the complex and in many cases, unpredictable set of interactions between the myriad of systems within it, a top down global whole-systems approach is the only meaningful starting point for considering sustainability. In this context, starting at the corporate level for example, makes no sense (Bebbington and Gray, 2001; Gray, 2009). The former approach would result in material and energy flows being placed in socioeconomic and biophysical context to see how each influences the other (Ruth, 2006). This approach can allow a clear demonstration of how any environmental gains achieved by closing say, a cement factory due to reduced overall consumption, are negated if carbon emissions are simply reapportioned to another activity via some carbon credit trading scheme. Similarly, banning Kenyan organic agricultural imports to the UK on the basis of excessive air miles, in the absence of a global approach to the issues involved, may precipitate other negative unintended (social and economic) consequences such as destroying small farmers livelihoods (Lohmann, 2009). Characteristics of this new paradigm would include a holistic, integrative, consensual, decentralized and systemic approach which seeks interdependence and is based on community, as opposed to being purely rational, analytical, individualistic, corporate, centralized and mechanistic (Taylor & Taylor, 2005). Until the global mindset has fully embraced this new paradigm, top down initiatives based on incorporating externalities, such as Kyoto, are likely destined to fail (Prins and Raynor, 2007; Lohmann, 2009).

1.2 Sustainability versus reduced unsustainability

In common with society in general, a large proportion of engineers do not still appear to recognise the implications, economically, environmentally and in particular socially and ethically that the transfer to a sustainable pathway represents (Segelàs et al., 2008). A degree of convenient complacency appears to prevail whereby *less* unsustainable systems, activities or processes are routinely labelled as being "sustainable". Such claims, which are essentially nothing more than *"fairy tales to help children sleep at night",* may be usefully employed as marketing devices but they serve to lull society into a false and ultimately potentially perilous sense of security (Gray, 2009). A "business as usual" approach, even if accompanied by some well meaning incremental modifications and improvements will not be sufficient to divert from the current "collision course", instead merely slowing down the advance towards inevitable destructive collision, while still failing to divert from it. In addition, incremental progress in terms of reducing unsustainability is often accompanied by a process known as rebound, whereby for example, gains in efficiency or through practical changes are merely offset by greater consumption levels (Binswanger, 2001; Clift, 2006; UKERC, 2007). This of course, benefits business since it generates more economic activity. Indeed much organisational reporting on sustainability tends to reflect how organisations would *like* to envisage sustainability rather than reflecting any actual achievement of sustainability (Milne et al., 2006; Gray, 2009). Such an approach aligns with the dominant social paradigm (Kilbourne et al., 2002) as it can be readily incorporated into a "business as usual" approach (Bebbington, 2001; Moneva et al., 2006). There is an inherent and inconvenient contradiction between the consumption related goals of business and the ultimate goal of the waste pyramid, which is to "avoid" consumption (Figure 2). This raises the possibility that the current conventional organisational business model may be incompatible with a sustainable societal paradigm. Business therefore typically prefers to envisage a weak form of sustainability which *"allows human-made capital to substitute for natural capital"* unlike strong sustainability which does not (Dresner, 2002). For example, British retailer Marks & Spencer, through it's albeit worthy "Plan A" initiative, makes the claim that it is aiming to be a carbon neutral organisation by 2012 (Marks & Spencer, 2008). Taking a whole systems global approach, it is virtually impossible to envisage how a retail organisation, operating with traditional manufacturing processes, supply chains and organisational structures in place, and in a society which values energy and materials at a fraction of that of labour (one barrel of oil contains the equivalent of 10 years labour yet costs a miniscule fraction of this) can claim to be sustainable. Indeed it is difficult to see 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 the whole operation is carbon neutral, regardless of the number of trees planted to offset carbon emissions. 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 while still accommodating the needs of several billion humans as well as its entire biodiversity. At any rate, this approach appears to be a mere carbon accounting exercise as opposed to one incorporating the broader issue of sustainability, in particular with respect to the social and environmental spheres. A broader point here is that organisations operate within the society/world they inhabit, and it is virtually impossible to unilaterally achieve sustainability in the former if the latter is systemically unsustainable. In short, since sustainability is a systems based concept upon which any analysis must begin at the global scale, it is virtually impossible to measure it effectively by starting at the organisational level (Bebbington & Gray, 2001; Moneva et al., 2006; Gray, 2009). Indeed attempts to date to comprehensively account for sustainability amount to at best an unfinished narrative (Bebbington et al., 2007; Frame and Cavanagh, 2009). Of course the current conventional organisational business construct appears in many ways incompatible with the creation of a sustainable society, particularly when it seeks to *"release shareholder value"* as its bottom line, that is, unless shareholder value is to be interpreted in the broadest possible sense whereby it might strive to incorporate *"activities that ensured shareholders might still be alive"* (Gray, 2006). Otherwise, despite the contention of businesses, *"it is highly unlikely that businesses can be sustainable"* (Bebbington and Gray, 2001), certainly on a "business as usual" basis. Whereas a new sustainability informed paradigm together with speedy incremental change may lead to some degree of success, any amount of marketing spin based on some very weak and malleable conception of sustainability will certainly not.

Figure 2 The waste pyramid

The popular conceptualisation of sustainability, as something that is in fact "reduced unsustainability" appears to be based on the dominant social paradigm whereby *"our collective cultural memory of the usefulness and usability of natural and man-made resources is independent of any sense of limits"* (Dewberry and de Barros, 2009). Thus this conceptualisation of sustainability is one which is *"rooted in a linear economic system driven by efficiency that allows only for relative improvements in ecological and social well-being"*, and though this may be an inevitable consequence of the pervasive societal construct, there is nevertheless an urgent need to *"shift emphasis to a more radical position that encompasses the societal case and the natural case, operating within the Earth's carrying capacity"* (Dewberry and de Barros, 2009).

1.3 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 (Woodall, 2003; Economist, 2005). Yet, while this analysis had widespread support, most governments, central bankers, bankers, businesses and individuals largely continued to operate in a "business as usual" manner, riding on the strong property fuelled economic growth rates that continued unabated for a number of years thereafter, taking the opportunity to expand businesses and take ever larger profits, in the hope of ultimately achieving a "soft landing". Even when the downturn came, it was initially met with incredulity by most, 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. 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 has latterly been called a "great recession", and where it has been claimed that *"the global economy might be at some kind of tipping point"* (BIS, 2008).

We appear, in many respects, to be somewhere 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 (Brown, 2003). Nevertheless, human society is generally carrying on with a "business as usual" approach, drifting between mild concern, hopeful and/or misplaced optimism, failure to comprehend the enormity of the situation, complacency, disbelief and denial. When US Energy Secretary Stephen Chu reveals that he doesn't feel *"the American public has gripped in its gut what could happen"* (Tankersley, 2009) he could just as accurately be describing the global populace. 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, unless and until there is severe and rapid deterioration. We are often only jolted into action by severe and paradigm shifting events, by which time the first responses often include disorientation, denial, squabbling and hopelessly inadequate firefighting measures. Should we not have achieved the aspired to *"soft landing to sustainable society"* (Arai et al., 2009) before the earth finally reaches climatic and ecological tipping points, any current economic woes will appear wholly insignificant by comparison to the effects (ecologically, socially and economically) of the resulting shortages of resources and basic needs in addition to accelerating climate change driven by an ecosystem in significant non-equilibrium. 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. Even then, there is the oftentimes not insignificant hurdle of aligning behaviour with outlook or intentions, particularly if the required behaviour is personally inconvenient and appears to be undertaken only on an individual basis, while resulting in some ill defined long term common good (Arbuthnott, 2009). This only serves to underline the imperative to work together to find a sustainable pathway. To do this we must have visionaries and leaders who can help chart a way forward. Engineers are potentially well placed on all these fronts and therefore are potential and obvious key players. Chemical engineers are particularly suited given their understanding of material and energy systems.

2. SUSTAINABILITY AND ENGINEERING; A NEW PARADIGM

2.1 Chemical Engineering perceptions

While some 62% of the customers of the aforementioned retailer either *"can't see the point"* or feel a sustainable future is *"not their problem"* (Marks & Spencer, 2008), it appears that the situation among chemical engineers may not be all that different. For example, a large minority (44%) of respondents to an online IChemE survey published in the May 2009 edition of the institution's TCE magazine believed that the UN (and presumably the UK's chief scientific advisor) *"is just scaremongering"* when it points to future global water shortages (TCE, 2009). Additionally, a majority (54%) of respondents to a corresponding survey published in the May 2007 edition indicated that they believe that sunspot activity rather than anthropogenic activity is the principal cause of climate change (TCE, 2007). Interestingly, this compares with 42% of European citizens who either feel that CO_2 emissions either have a marginal impact on climate change (30%) or are not sure if it does (12%) (European Commission, 2009). Similarly, very few of the twenty five US academic and industry "visionaries" looking ahead to chemical engineering through the next quarter century identified sustainability related issues as the most important emerging considerations (Westmoreland, 2008), while Ziemlewski (2008) reports scepticism among a number of respondents to an AIChE survey with respect to climate change related issues. This is perhaps unsurprising given the limited role that sustainability has played in engineering education to date. In this context it is interesting to note that the predicted importance of sustainability to their own practice over the next quarter century as conceived by chemical engineers is inversely proportional to respective years since graduation (Ziemlewski, 2008).

Chemical 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 play a leadership role in redesigning society in a sustainable manner. 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 under constraint"* (NAE, 2004) (e.g. economic, environmental, safety, ethical) to one where genuine sustainability (and all that this entails) becomes the very *context* of engineering practice, the lens through which all engineering practice is filtered.

2.2 Increased recognition of issues surrounding sustainability institutionally

Over the past two decades, there has been an increasing realisation among the engineering profession of the pressing need to create a sustainable global society. This has manifested itself most visibly through the respective representative professional institutions. Engineers Australia developed a policy on sustainability in 1994 which required that *"members, in their practice of engineering, shall act in a manner that accelerates achievement of sustainability"* (Carew and Mitchell, 2006). In 1997, eighteen national and international institutions representing the chemical engineering profession globally signed the London Communiqué which pledged *"to make the world a better place for future generations"* (Batterham, 2003). This was followed up in 2001, at the 6th World Congress on Chemical Engineering, where twenty chemical engineering institutions signed the Melbourne Communiqué (2001), a one page document committing each of them to work towards a shared global vision based on sustainable development.

The IChemE proposed a vision for the profession which clearly demonstrates the link between applying a (material and energy balance) systems approach and achieving a sustainable society in its publication on Sustainability Metrics (IChemE, 2001);

> *"The laws of conservation of mass and energy are basic principles utilised by engineers. However the results of manipulating the resources of the planet through these principles have consequences for the global eco-system. ..It is clear that we have to be less profligate in our use of non-renewable resources if*

> *the planet is to be fit for future generations to live on. We must also be more aware of the consequences of our activities for society at large."*

The metrics are themselves an example of the approach favoured by neoclassical environmental economists (Illge and Schwarze, 2009), whereby (social and environmental) "externalities" can be expressed in equivalent economic terms and awarded appropriate accounting costings in the belief that the market can do the rest. Cost benefit analysis accounting and carbon market trading are example applications of this approach (see Lohmann, 2009).

The United States National Academy of Engineering has formulated its vision of the Engineer of 2020 (NAE, 2004). Its report outlines a number of aspirational goals where it sees the profession taking a more central normative role in society. These include facilitating design *"through a solid grounding in the humanities, social sciences, and economics"*, rapidly embracing new fields of endeavour *"including those that require openness to interdisciplinary efforts with nonengineering disciplines such as science, social science, and business"* and taking a lead in the public domain by seeking to influence public policy positively. Critically, the report calls for engineers to be informed leaders in sustainable development and notes that this *"should begin in our educational institutions and be founded in the basic tenets of the engineering profession and its actions"*. It suggests that engineering curricula be reconstituted *"to prepare today's engineers for the careers of the future, with due recognition of the rapid pace of change in the world and its intrinsic lack of predictability"*.

The Royal Academy of Engineering published a set of twelve *"Guiding Principles"* for engineering for sustainable development (RAE, 2005), in a document which also provided examples and applications for curriculum implementation. The RAE has also sponsored a visiting professors scheme in the UK from 1998 *"to embed the topic of engineering for sustainable development into engineering course and not to create a separate subject"* (RAE, 2005).

The Institution of Chemical Engineers (IChemE), a signatory body at London and Melbourne, followed through as part of these commitments by drawing up "A Roadmap for 21st Century Chemical Engineering" (IChemE, 2007). In practice, this is a type of strategic plan for chemical engineering largely based on moving towards a sustainable future. Each of its six themes, which include *“sustainability and sustainable chemical technology”* and *“health, safety, environment and public perception of risk”,* incorporates strong sustainability threads. A progress report on the roadmap was published in 2008 (IChemE, 2008).

Engineers Australia launched a formal sustainability charter in 2007 (Engineers Australia, 2007), taking a broad view, purposely placing a particular emphasis on the social sphere, an area where engineering has traditionally been weakest (Segalàs et al., 2008). The charter proposes the institution’s belief that *“sustainable development should be at the heart of mainstream policy and administration in all areas of human endeavour”.* It also notes that achieving this will not be easy and *“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 recognising 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.

Engineering Council UK (ECUK, 2009) has set out six guidance principles on sustainability for the engineering profession which, it suggests respective professional engineering institutions may wish to use in developing guidance for their members. These include (number 3) doing *more* than just complying with legislation and codes currently in place and (number 5) seeking multiple views to solve sustainability challenges. These principles provide an implicit admission that the professional codes do not go far enough as well as a humble acknowledgement that engineers do not, and can not have all the answers to the problems arising from our unsustainable societal construct, nor can they alone turn things around. Indeed, they also suggest that engineers should use their influence to help drive future legislation and codes. ECUK clearly envisages a broad, ambitious and integrative role for the 21st century engineer and suggests;

> *“the leadership and influencing role of engineers in achieving sustainability should not be under-estimated. Increasingly this will be as part of multi-disciplinary teams that include non-engineers, and through work that crosses national boundaries.”*

2.3 Professional institutions and programme accreditation documentation

Accreditation guidelines are important because they play a vitally important role in achieving change. The Royal Academy of Engineering (RAE, 2007) highlighted this in their report on educating engineers for the 21st century when they recommended that *"the accreditation process for university engineering courses should be proactive in driving the development and updating of course content, rather than being a passive auditing exercise".* If the initiatives proposed by the various institutions (reports, communiqués, charters, codes of practice, roadmaps, principles, etc.) which place sustainability at the core of engineering are to be carried through to their logical conclusion, then one might reasonably expect that this would be reflected in respective accreditation documentation and hence through accredited programmes. Over time this would be reflected in the approach of graduate engineers themselves.

In this context, the 1997 report of the Joint Conference on Engineering Education and Training for Sustainable Development in Paris called for sustainability to be *"integrated into engineering education, at all levels from foundation courses to ongoing projects and research"*. It also called on engineering organizations to *"adopt accreditation policies that require the integration of sustainability in engineering teaching"* and notes that *"retraining all faculty members"* will be *"important in implementing the new approach"* (Paris, 1997). The 4th International Conference on Environmental Education in 2007 called for a new sustainability informed paradigm which will require *"an educational framework that not only follows such radical changes, but can take the lead"* and suggests that achieving this will involve *"fundamental changes in the creation, transmission and application of knowledge in all spheres and at all levels"* (ICEE, 2007). A paradigm shift in engineering education is thus required to enable the complete implementation of these recommendations (Mulder, 2006), which would result in some degree of programme reform or at least a recalibration of focus (Mitchell, 2000; Gutierrez-Martin and Hűttenhain, 2003; Venselaar, 2004; Bucciarelli, 2008; Holmberg et al., 2008).

While the efforts by chemical engineering programmes to incorporate strong sustainability elements into their programmes (often in conjunction with increased levels of active and problem based learning) have been well received by the professional institutions (e.g. see Gomes et al., 2006; Harris and Briscoe-Andrews, 2008), the onus remains with the institutions themselves to lead if sustainability is to be fully and universally integrated into the curriculum (Batterham, 2003). However, despite the initiatives outlined above, the work of the institutions in repositioning sustainability as a *"core operating principle"* (Mitchell, 2000) has not yet fully trickled down into programme accreditation documentation. Most accreditation guideline publications require sustainability to be covered along with a number of other non-core issues such as health and safety, economics, etc., but none, to the authors' knowledge, explicitly require that sustainability should actually permeate right through the programme; i.e. that it should be the context, or a lens through which all programme material should be filtered.

IChemE (2005) prescribe that graduates must achieve specified learning outcomes under five headings; three of these explicitly mention sustainability, though it is generally mentioned as one among many considerations (health and safety, business, ethical, etc.) rather than as a wholly intrinsic consideration running though all programme outcomes. The national capstone accreditation body that the IChemE operates under, Engineering Council UK, publishes professional engineering accreditation programme requirements based on programme learning outcomes as part of the UK Standard for Professional Engineering Competence (UK-SPEC) (ECUK, 2008) "Design" is one of the five generic learning outcomes listed, and it is defined as *"the creation and development of an economically viable product, process or system to meet a defined need."* Pointedly, there is no requirement for ecological or social viability here and sustainability is only mentioned within one of a number of learning outcomes associated with design; *"identify constraints including environmental and sustainability limitations, health and safety and risk assessment issues".* Another generic learning outcome involves the *"economic, social and environmental context",* and this requires, among others, that engineering graduates possess an *"understanding of the requirement for engineering activities to promote sustainable development".*

Among other national professional accreditation bodies, Engineers Australia (2006) promote a similar approach whereby professional engineering competencies are divided into three headings; knowledge base, engineering ability and professional attributes. Sustainability is emphasised under the second of these. Engineers Canada (2008) require that graduates satisfy a list of twelve general attributes, one of which; *"impact of engineering on society and the environment"* mentions sustainability, and then just in terms of understanding concepts and interactions. In the USA, ABET (2007) have eleven requirements of graduates under its Citerion 3 (Assessment) outcomes, 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"* and *"the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context"*. This is the only place that sustainability is mentioned, either among the other 10 Criterion 3 outcomes or among Criterion 2 (Educational Objectives) and Criterion 4 (Curriculum) outcomes, though it *could* be incorporated into several of them (Kelly, 2008). Engineers Ireland (2007) simply advise that undergraduate degree level programmes *"need to develop an awareness of the social and commercial context of the engineer's work"* including an understanding of the constraints imposed by the environment, codes of practice and others. The Engineering Council of South Africa makes similar provisions in terms of being *"critically aware"* and *"competent"* to assess the impacts of engineering activity on a number of levels such as for example, social, legal, health, safety, and environmental (von Blottnitz, 2006). Each of these approaches are still some way off the various high level declarations and initiatives of the various engineering institutions as outlined in the previous subsection, whereby a sustainability informed paradigm is envisaged as being at the heart of engineering design and practice.

It is likely however that this situation will change with the next iteration of accreditation documentation, in line with the ever more progressive top down stances being taken by the various institutions, in particular as the consequences of our unsustainable society come into sharper focus with time. Moreover, despite the limited progress made over the past decade in embedding sustainability into curricula, it is likely that regardless of the professional institutions, progress will accelerate over the next two decades as institutions will not wish to see their respective programmes fall behind international norms (Desha et al., 2009).

2.4 Implications of a sustainable paradigm for chemical engineering

While realigning curricula to embed sustainability systemically presents many difficulties (Holmberg et al., 2008), it nevertheless has the potential to become the next frontier in engineering education (Favre et al., 2008). Such a development would ensure a greater degree of reflection on attributes related to values, ethics, complexity and the critical thinking required to relate various interests; social, political and environmental with the technical and economic throughout the curriculum (Bucciarelli, 2008; Segalàs et al., 2008). It would thus help mould an outward looking, collaborative seeking professional engineer with both an ability and desire to engage with other professions and groupings who may have alternative and/or deeper understandings of some of the elements of sustainability (Batterham, 2003; Gutierrez-Martin and Hűttenhain, 2003; Clift, 2006). The collaborative approach that this sustainability informed paradigm would promote would necessarily bring chemical engineers into closer contact with fellow stakeholders. These include natural, environmental and social scientists, economists, accountants, geographers, toxicologists, sociologists, psychologists, philosophers, planners, politicians and policy makers as well as extended peer communities, who as legitimate stakeholders may bring additional local and anecdotal knowledge or insights to the issue at hand (Healy, 1999). The problem at hand for the chemical engineer therefore moves from a purely technical one with well defined boundaries and a well defined solution set to a larger ill-defined and altogether messier one with numerous possible options. Subjective resolution necessarily supplants “objective solution”. Sustainability issues inhabit the realm of the so called “wicked” problem (Rittel and Webber, 1973) where problem boundaries are typically unclear and/or contested to start with but where resolution (as opposed to “solution” as in the case of well defined, “tame” problems) is ultimately sought through broad consultation and deliberation. Such problems are typically characterized by uncertainty, complexity and sometimes also contradiction with respect to both problem formulation and resolution. They involve factors which are not easily quantifiable; both known factors which are not easily quantified (“known unknowns”) and unknown factors (which therefore cannot be incorporated) whose effect could not be easily quantified even if they were identified (“unknown unknowns”). While “unknown unknowns” will always be a part of wicked systems, systems designed in defiance or ignorance of these are both fantastic and ultimately doomed to failure, in which case their ultimate discovery (e.g. following disaster) proves painful (Ravetz, 2006). They also incorporate contradicting needs, preferences and values among a broad range of stakeholders (Turnpenny et al., 2009), thus necessitating a certain degree of subjectivity around any resolution. In addition, the consequences of any actions taken in an attempt to resolve the issue(s) cannot be predicted due to the degree of uncertainty that is inherent in such complex systems. It has therefore been suggested that the answers to such problems lie in the realm of “post normal” science (Funtowicz and Ravetz, 1993; Ravetz, 1999; Ravetz and Funtowicz, 1999). In tackling such problems, it is necessary that both scientific/technical experts and extended peer communities each approach the problem and accompanying dialogue *“in good faith”* (Ravetz, 2006), while being respectful of each others respective backgrounds and expertise. Sustainability clearly lies within this realm (Ravetz, 2006; Frame and Brown, 2008). A repercussion of this is a “new role” envisaged for chemical engineers (Clift, 2006). This role could be characterized as that of the “new engineer”, a concept developed by Beder (1998) and elaborated by Conlon (2008) among others. This is a new, unfamiliar and perhaps daunting place for engineers equipped only with traditional skills and outcomes, though conversely a potentially far more exciting, influential, society transforming and fulfilling place to be. Here engineers can act as an "honest broker" and use their particular skills and perspectives to engage with other stakeholders while also being open to the expertise and concerns of others (Mitchell et al., 2004) as opposed to simply being uncritical agents of economic and technological development.

2.5 Sustainability in engineering education; the current situation

In the USA most engineering programmes *"have made only minor progress, if any, in increasing exposure of students to sustainability issues"* (Davidson et al., 2007). A similar situation pertains throughout the rest of the world (Azapagic et al., 2005; Desha et al., 2009; Hazelton et al., 2009), and it has been suggested (Porritt, 2007) that;

> *"Modern undergraduate engineering programmes rarely reflect such important issues, and many graduates have a limited understanding and experience of their potential contributions to society as engineers, or indeed the wider impact of their professional decisions."*

It has also been suggested that the problem lies in the academics themselves as much as in the programmes they teach (Jowitt, 2007);

> *"It's meant to be embedded ..if they don't put sustainability in[to curricula], they wouldn't be accredited. But I wouldn't say we're up to pace yet. We need to get it better; it needs to be embedded in the minds of the academics and not just the students, so there's a big challenge."*

On the other hand, there are a number of organisations globally who are pushing for a sustainability embedded engineering curriculum, including the Center for Sustainable Engineering (involving Carnegie Mellon University, Arizona State University and the University of Texas at Austin) in the USA (Allenby et al., 2007) and the European based EESD Observatory (EESD Observatory, 2008). In addition, there are also a number of online resources aimed at aiding engineering educators develop sustainability themed modules through their programmes and at embedding sustainability throughout curricula (e.g. TNEP, 2004; Loughborough University, 2004; The Cambridge-MIT Institute, 2006). As part of this effort, the Engineering Education for Sustainable Development (EESD) Observatory, a group created by three European technological universities to the forefront of education for sustainable development; UPC Barcelona, Spain; TU Delft, The Netherlands and TU Chalmers, Sweden, publishes a biennial survey measuring *"the extent that sustainability is embedded in European engineering education"* (EESD Observatory, 2008). Participating institutions are ranked based on five criteria drawn from the Declaration of Barcelona (2004): 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. The EESD survey is self reporting however, and this leads to a situation whereby all institutions for example are (self) credited with either completely embedding sustainability into their engineering programmes (100% rating) or not at all (0% rating). This all or nothing scenario does not concur with literature evidence among those who have attempted to embed sustainability into engineering programmes (Perdan et al., 2000; Gutierrez-Martin and Hüttenhain, 2003; Mulder, 2004 & 2006; Fenner et al., 2005; Kamp, 2006; Gomes et al., 2006; Favre et al., 2008; Holmberg et al., 2008; Hayles and Holdsworth, 2008; Tomkinson et al., 2008; Quinn et al., 2009). In general each of these have found the exercise to be a complex and incremental process. Indeed it would be hard to see how anything that is at once so transformative, contested, "wicked" and multidisciplinary in nature could possibly be otherwise. Of the five factors considered for the EESD index, it is that of embedding sustainability into the (chemical) engineering curriculum (as recommended by the aforementioned 1997 Joint Conference), which forms the focus of the remainder of this paper.

3. ENGINEERING; IMAGE, ROLES AND RESPONSIBILITIES

3.1 Public image of engineering

The engineering profession registers a startlingly low level of recognition and understanding on the public's radar. It has been suggested that the image and status of the engineer is declining, and they are seen as generally having poor social skills, being politically naïve and prone to finding themselves at the centre of controversies they don't understand (Beder, 1998). This results in engineers often being oblivious to the wider social implications of decisions, whereby they perceive problems only in purely technical terms as unique optimisation exercises. This role allows engineers therefore to happily fit into the role of experts within technocratic governments and organisations (Mulder, 2006). In excess of half the engineering students surveyed in a recent study at Imperial College London conceded that they themselves did not know what an engineer was before entering their programme (Alpay et al., 2008). Another British study of attitudes to engineering among the public confirmed this profile; perceptions of engineers and engineering were quite vague and attitudes towards engineering were generally mixed, with both positive and negative feelings expressed (RAE & ETB, 2007). While it was felt that engineers were responsible for providing many modern conveniences, they were also held *"responsible for key problems in society, such as climate change".* Engineering was also perceived to be *"part of a type of commercialism that acted in the interests of money and progress rather than the good of people".* It may be that the public image of engineering helps to attract a certain type of student, and the curriculum (and subsequent professional practice and ethos) reinforces this approach in a self perpetuating cycle.

3.2 Perceived and actual societal roles and responsibilities of engineers

With respect to engineers own conceptions of their roles, two distinct modes are apparent (Bucciarelli, 2008). One is that of the value neutral "gun for hire"; essentially "paid hands" who envisage their role as primarily to serve their respective paymasters. The alternative mode dictates that engineers envisage an altogether broader remit incorporating an explicit ethical commitment to social responsibility. The former mindset Bucciarelli argues, is *"implicit in all of our teaching in the core of our disciplines".* Proponents of this mode would feel uncomfortable with engineers dwelling on the "soft" side of problems. This viewpoint has presented significant resistance against embedding sustainability into engineering curricula (Holmberg et al., 2008). It may also typically conceive engineering as being apolitical (though conforming to the dominant techno-economic focused paradigm). On the other hand, failure to envisage a broader remit for engineering, and in doing so failure to embrace a sustainability informed paradigm, has contributed to *"concern that the status of engineering is being undermined as engineers are identified with environmentally damaging technologies"* (Conlon, 2008).

Sustainability informed practice would align with the latter mode, thereby bringing engineers into new, less familiar territories and into contact with other professions and stakeholders, and ultimately more in concert with the needs of society (Mitchell, 2000; Batterham, 2003; Symkowiak, 2003; Chau, 2007; Conlon, 2008; Jennings, 2009; Allenby et al., 2009). In this way the engineer can draw upon much more than just dispassionate objectivity; they can harness the additional store of *"intuition, feelings and passion"* that only comes thorough making both *"physical and emotional connections"* with the issue at hand, thereby achieving a degree of *"dynamic objectivity"* (McIsaac and Morey, 1998). Chemical engineers generally profess a positive disposition towards the principles of sustainability, indeed more positive (by their own estimation) than their employers (Furlong, 2004). However this masks a wide spectrum of views among practitioners on how far their responsibilities go; indeed there isn't widespread agreement among engineering academics on how they conceive sustainability (Carew and Mitchell, 2006; Lundqvist and Svanström, 2008). Accordingly IChemE (2001) have appeared to concede that chemical engineers have in the past fallen short, suggesting that *"moving towards the goal of sustainability"* will require the profession *"to examine and improve other aspects that have not traditionally been given much attention, at least by practicing engineers."* Embedding sustainability in such a way that it is *"woven throughout the curriculum"* (von Blottnitz, 2006) would go some way towards addressing these shortcomings by adjusting the collective philosophy of the profession. However, agreement on doing this or to what extent is difficult to achieve and progress can be slow. Some of the universities to the forefront in terms of embracing sustainability into their curricula over the past two decades have faced substantial difficulties in integrating it into their respective curricula, not least due a narrow conception of sustainability among scientific faculty (Holmberg et al., 2008). Moreover, on the occasion of its one hundredth anniversary, the AIChE suggested redefining their constitutional definition of chemical engineering (Evans et al., 2008) but they chose not to use this opportunity to introduce the concept of sustainability.

3.3 A profession misunderstood?

Chemical engineers will often protest that they are misunderstood by wider society given that they are responsible for developing and designing many of the conveniences associated with modern society that help people enjoy a better lifestyle at reasonable cost; for example, plastics, drugs, cosmetics, mass food processing, clean water, fuel, etc. They are often at a loss to understand why chemical engineers do not have a better reputation or standing among the public at large, and are held *"responsible for key problems in society"* (RAE & ETB, 2007). It must be recognised that when viewed in the context of the prevailing societal construct over the past century and a half, the achievements of chemical engineers are indeed very substantial. However, in the context of a sustainability informed paradigm, these achievements may not measure up quite as well. Redclift (2005) for example, could just as easily have justifiably substituted *"chemical engineering"* for *"management"* when he observed;

> "*With hindsight we can see that each scientific problem resolved by human intervention using fossil fuels and manufactured materials is conventionally viewed as a triumph of management, and a contribution to economic good, when it might also be seen as a future threat to sustainability."*

Perhaps chemical engineers are not so much misunderstood therefore, but instead need to reflect themselves on the profession's own values and actions, with the aim of better understanding what is it chemical engineering should be about and what sort of society we want and need to create. While there was a general expectation that in the wake of the large scale engineering projects under Hoover and Roosevelt in the USA that engineers would thereafter more explicitly consider societal needs (Grayson, 1993), this did not happen to any appreciable extent and what engineers often *"failed to recognise was that the issue at stake was not always a scientifically/mathematically solvable optimisation problem, but a choice between irreconcilable norms and values"* (Mulder, 2006). Taking a broader vision would not only be a liberating experience for chemical engineers, but would also help restore much of the prestige and social standing enjoyed during that golden age of engineering, during the century following the beginning of the industrial revolution. More acutely, such an approach is a pressing requirement for the 21st century engineer.

4. EMBEDDING SUSTAINABILITY IN CHEMICAL ENGINEERING PROGRAMMES

4.1 Dedicated sustainability modules

Dedicated modules and elective streams are useful in enabling engineers understand the language of sustainability; its concepts, the role of the political, natural and social sciences and the engineer's relationship to them (Allenby et al., 2007; Kelly 2008) and in this way, develop a better appreciation of major dilemmas which are best addressed by, and in cooperation with, other disciplines (Davidson et al., 2007). Dedicated modules and streams also provide a focus for sustainability on a given programme and explicitly demonstrate a clear commitment to accreditation bodies and potential recruits on behalf of educators towards incorporating sustainability.

4.2 The need to embed sustainability

Dedicated modules and elective streams alone are not in themselves sufficient however to demonstrate how sustainability should be the *context* through which twenty first century chemical engineering must be practiced. To do this programmes must inherently and consistently demonstrate the need for sustainable practice (Perdan et al., 2000; Azapagic, 2005). Extra modules or electives simply bolted on to an existing curriculum, without the concept being rooted throughout the programme provide a *"less than satisfactory approach to the education of engineers"* (Rahimifard and Clegg, 2008). They are also likely to be perceived (particularly by sceptical and disengaged academics) as yet another addition to an already overburdened programme. On the other hand, embedding sustainability throughout the curriculum by incorporating this paradigm through individual modules would help ensure the required *"greater degree of detail ..so that students have to think very carefully about the issues at hand"* is provided. This would help address the difficulty that *"references to sustainable development are for the most part still at too high a level"* (Desha et al., 2009). A programme wide integrated approach would also serve to elicit greater levels of engagement with respect to sustainability among (future) graduates through their professional practice, since concrete examples (particularly ones which demonstrate how it is possible to make a difference or exhibit perceived control), case studies and specific implementation intentions which relate to practice has shown to be more effective at generating behavioural change than generalised abstractions and principles (Arbuthnott, 2009).

The sustainability informed ethos should be front ended within the programme and the introductory module or unit on chemical engineering is an ideal place to introduce the concept through for example, material and energy balances and professional ethics. It should then continue right through the programme in a coordinated and coherent manner. It is therefore of vital importance that there is buy-in among all or at least almost all the teaching staff on a given programme, so that each can develop their own modules or units so that they are taught through a sustainability informed lens. This may require some discussion or education among teaching staff on the concept and issues surrounding sustainability as these are applied to chemical engineering, in a way that ensures staff buy-in, so that there doesn't arise a feeling that the incorporation of a sustainability informed paradigm through the curriculum is a mere trivial exercise driven by a small group of enthusiasts. For example, many academics may feel that a sustainability informed paradigm already exists across the (existing) curriculum, on the basis that it already advocates and seeks more efficient (and less unsustainable) processes (e.g. Gutierrez-Martin and Hűttenhain (2003); Bi (2005)). Less than 30% of engineering academics were rated by recent graduates (with two to ten years post graduate experience) in a British study as being in any way passionate in their attitudes regarding sustainability, while the rest were considered to be either disinterested (a majority overall) or showed some degree of hostility towards the concept (Meddings and Thorne, 2008). The same study indicated that preferred option of the graduates, at 60%, would be for sustainability to be integrated into the whole programme as opposed to exclusively through separate module(s).

4.3 Threshold concepts in chemical engineering education

A number of the fundamental tenets or "threshold concepts" (Meyer and Land, 2003) relating to chemical engineering are ideally suited in helping realise a sustainability informed paradigm. These concepts include material and energy balances (for the most part exclusive to chemical engineering curricula), the systems approach to which these constructs relate, the second law of thermodynamics and the associated concept of entropy. Armed with these tools, particularly when presented in a global context, the chemical engineer can build up an effective and straightforward conceptual model of the world which can be employed to envisage how (un)sustainable a given activity may be. Informed by this model, the chemical engineer is then well positioned to become a productive partner in the collaborative quest for a sustainable society with other professions, disciplines, stakeholders, 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 aim here is not in any way to dilute the technical content or rigour of core technical competencies, but instead to add value to their programme by enhancing students' understanding of these by providing a suitable (global) context. The additional insights and learning gained by this process can only serve to increase student motivation and enjoyment of their chemical engineering programme while offering a broader skill set. The remainder of this paper will involve examining some of the aforementioned threshold concepts, along with some examples of their application.

4.4 Material and energy balances

Material and energy balances are core threshold concepts for the chemical engineer, based on the laws of conservation of matter and energy. They are applied around given defined systems to determine material and energy flowrates throughout particular units, processes or systems. They are 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. In this way they can provide a straightforward overview of the nature of non-equilibrium for the global system and hence some appreciation of unsustainability since *"human sustainability is possible only when it follows natural laws of mass and energy balance"* (Pereira, 2009). Because material and energy balances are generally covered in the first year of the chemical engineering degree programme, typically as part of an introductory module, they are an ideal vehicle for introducing the concept of sustainability to students from an early stage. 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 way, and can easily grasp the rationale behind striving for a sustainable world. They can then be revisited later on in the programme in an applied manner in the form of life cycle analysis assessment for example, or through a systems engineering approach (Elliott and Deasley, 2007).

Figure 3 demonstrates a model of the biosphere, 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. Natural resources and the atmosphere - our natural environment are positioned outside the system boundary. This is therefore analogous to Figure 1, albeit more detailed. These are resources that 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, carbon dioxide and other compounds and elements not shown here without limit with imperceptible economic or societal consequence (such as for example, nitrogen through intensive fertiliser use), our society has in modern times outgrown this mode of operation. The sheer scale of the respective imbalances as a result of the material input and output flows across this system boundary are now so great, that the environment (that space which is outside the system boundary) is in the process of collapsing on many levels. Once a certain (tipping) point is reached, this will result in a rapid collapse of that which is within (human society; both economically and socially). 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, which in itself cannot be but in a certain state of non equilibrium (unless it supports no life processes). Rather a symbiotic relationship must be (re)established where flows are by and large balanced within a framework of sustainable non equilibrium or near steady state.

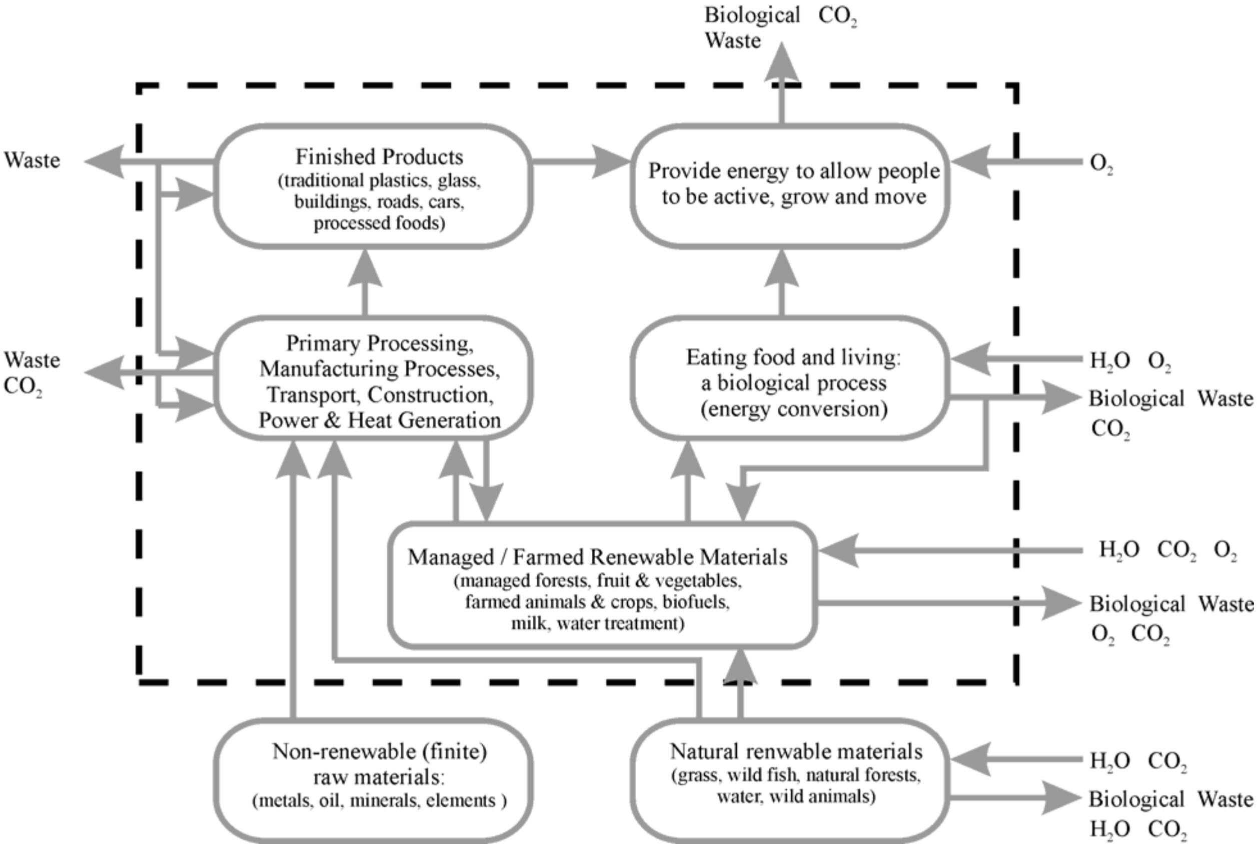

Figure 3 A systems approach to material flows in the biosphere

Of course Figure 3 can be redrawn to accommodate corresponding energy flows within society. While the global system that is the biosphere (i.e. all the contents of Figure 3, 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. 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 come 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 significant material imbalances across the system boundary through depletion of finite resources, creation of hazardous wastes and/or the addition of compounds such carbon dioxide.

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 4). While these sources may have finite limits, these limits have come nowhere near being tested to date. Clearly, for this to happen, great societal, economic and technological changes must occur. The technological aspect is in many ways the easy part; many of the required technologies either already exist or can readily be developed once an appropriately conducive economic, societal and regulatory framework is in place. 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 envisage a responsibility for engineers in informing and leading the required social, economic, regulatory and technological evolution to meet the requirements and expectations of society in a new and sustainable manner?

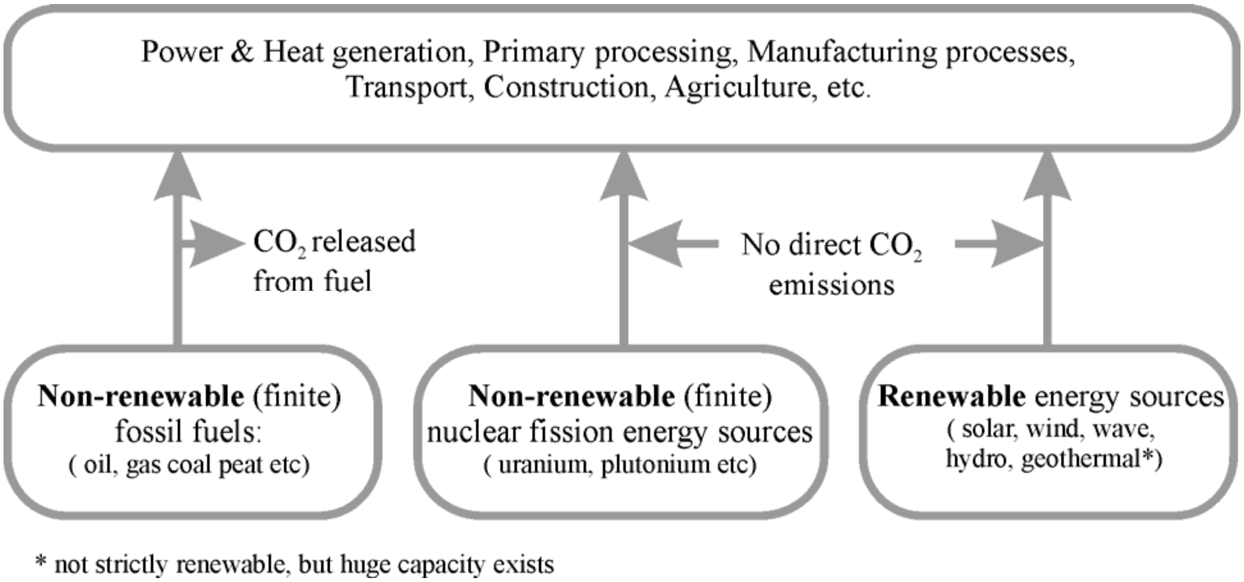

Figure 4 Sources of energy driving human activity

4.5 Entropy and the second law of thermodynamics

The second law of thermodynamics is one of the most elegant and profound laws of our universe. Whereas the first law of thermodynamics tells us that energy cannot be either created or destroyed, energy in itself has little value unless it is presented in a high quality, non-dispersed or low entropy form (Figure 5). 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 tend to deteriorate over time, once provided with sufficient activation energy.

The biosphere can be seen as an interrelated series of second law cycles where organisms give up their low entropy energy (e.g. a decomposing apple), which can be used to feed other organisms to allow the latter store energy and reduce entropy (e.g. the bugs which help decompose the appple). Such processes result in an overall net increase of entropy in the universe. 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. The inherent links between energy, entropy and sustainability (Norde, 1997) 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 (Hermanowicz, 2005), or the assertion that there is *"minimum entropy production in sustainable systems"* (Ho and Ulanowicz, 2005). The broader context having been established, the focus can then be switched to the process scale as appropriate.

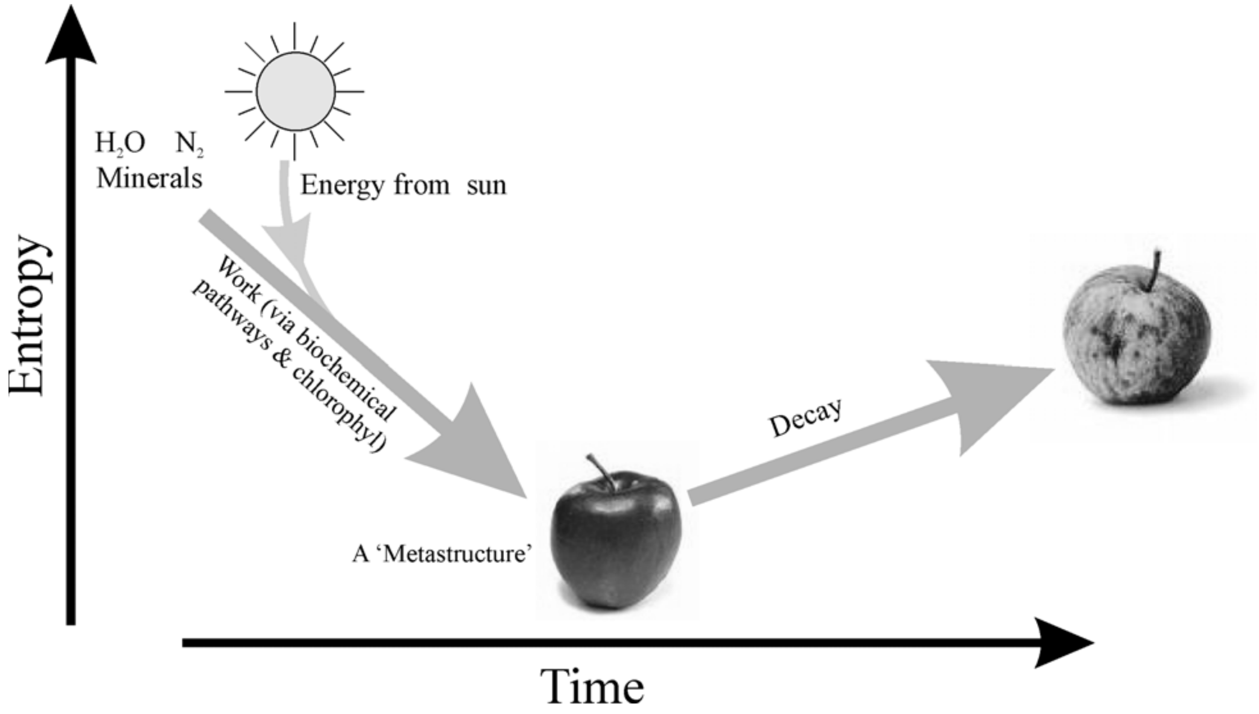

Figure 5 Changes in energy dispersal (entropy) associated with growing and rotting apple

4.6 Process and product design (innovation through sustainability)

All chemical engineering degree programmes have a final year capstone course which involves group design. 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 programme in a practical and applied manner. The traditional chemical engineering project involves designing a process to produce a given product; a bulk chemical, a pharmaceutical or food product are typical examples. 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 and design 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. A typical design exercise example is the production of the vinyl chlorine monomer (VCM), the precursor to the poly vinyl chloride (PVC) polymer (Gutierrez-Martin and Hűttenhain, 2003; Bi, 2005). Here, as part of the design exercise, students are required to investigate two options; one with an ethylene raw material, the other using acetylene. As part of this, a number of novel unit operations are considered which 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. While these are interesting and in some ways innovative studies, they remain firmly within the constraint driven 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.

A more appropriate question from a sustainability standpoint might not be simply: “What is the best way to produce vinyl chloride?” but rather; “Design a process to produce a material with the properties of PVC.” This leads to follow on questions such as; “Are there materials, and corresponding process, other than MVC/PVC that can take their place, that are sustainable, or at least, less unsustainable?” “Could for example, lactic acid, and the resultant biodegradable plastic polymeric lactic acid (PLA) take the place of PVC for many applications?” “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 (Byrne et al., 2004) or from thermoprocessible plastics produced by simple modifications of oxygenated biomaterials?” (Grassian et al., 2007). These are the questions which 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 not only while carrying out and researching their project but throughout their future careers. This also allows the undergraduate engineer develop an appreciation and capacity for research whereby they peer over the possibilities emanating from the cutting edge of scientific and engineering research. This approach is also likely to lead to greater innovation among aspiring chemical engineers. For example, graduates of this type of education may be more likely to consider designing a plant using micro reactors and micro-unit operations as opposed to at traditional large scale and hence push process design boundaries which have been traditionally left untouched due to a regulatory framework which has traditionally been perceived of being complicit with inertia. Chemical engineering graduates should then be more likely to carry this innovative spirit with them to the world of real engineering throughout their upcoming professional careers as they envisage a wider, more normative role in society for themselves where they can influence key production decisions and directions. Plastics companies who hire chemical engineers who see their role as merely “paid hands” to produce plastics more efficiently may find themselves without a market over time, and the chemical engineer they hired without a job. Chemical engineers who join plastic manufacturers, and who see their role as one which produces a product which meets a required specification for a given function, may help lead their organisation to continued success through innovation and new product lines.

There is potential for incorporating life cycle assessment (LCA) too into the design project as a method for quantitatively assessing environmental unsustainabilities in a proposed design. The LCA would give the students an insight into the full environmental impact of a proposed design and could inspire them to develop an improved design which has better environmental performance.

Such a broader sustainability informed approach will engender a greater level of excitement and possibility among young engineering students and graduates. It can also help 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 (Benyus, 2002, Benyus and Pauli, 2009).

Moreover, a sustainability embedded curriculum will not rely so heavily on the final year design project to draw together a number of topics from the degree programme in a holistic and integrated way in what has been characterised as a bottom up approach (Hargroves and Smith, 2006). Instead, it can accommodate a corresponding top down global approach where students can be presented with whole engineering problems throughout the programme from year one and invited to pull them apart, ask questions on the social need, develop criteria for describing and evaluating such problems as well as possible solutions which incorporate social, economic and environmental aspects as well as technical.

4.7 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 (Bucciarelli, 2008). Bucciarelli (2008) argues that this approach 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"*.

Bucciarelli (2008) suggests reform of the engineering curriculum *"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 Conlon (2008) who, in addition notes gaps in engineers' conceptualisation of sustainability, particularly the social element; *"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."* Such discourse is not unique among engineering; a sustainability informed paradigm has been proposed as a suitable vehicle for developing an enhanced ethical maturity among graduates of accounting and other disciplines (Gray et al., 1994; Oliveira de Paula and Cavalcanti, 2000).

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 wicked sustainability related problems. Such an approach can also provide chemical engineers with a greater sense of self-awareness and motivation than a series of well defined formulaic and individualistic case studies on professional ethics.

5. A NEW PARADIGM; NEW OPPORTUNITIES

5.1 A central role for chemical engineering

There are a number of fundamental reasons for suggesting why chemical engineering, indeed all engineering, should play the central role in reconstructing society in a sustainable manner. On the most basic level, it is a simple fact that the engineering systems approach that chemical engineering applies through the laws of conservation of matter and energy, is a fundamental basis for assessing environmental sustainability. The second law of thermodynamics and the related concept of entropy is also central to understanding energy flows through the natural system that is the earth. By examining these issues in relation to the creation of a sustainable society, engineers can play a lead role in communicating the physical constraints and means to creating such a society with other professions and stakeholders. For example, a commonly held view among neoclassical environmental economists is that *"sustainability does not require restrictions on material consumption"* (Illge and Schwarze, 2009). Similarly, *"few economics textbooks teach undergraduates or graduates that materials and energy are essential inputs into any production process; instead, most include models that deal only with labour and capita"* (Ruth, 2006). This demonstrates why chemical engineers can (and must) work with economists, accountants and others to create a new paradigm which recognises that continually increased levels of consumption, whatever about economic growth, is not compatible with a sustainable society. Of course chemical engineers can also learn from others too, in a way that will substantially enrich both society and the profession, while improving both the public image and status of the latter.

A second reason for placing engineers in a central role in the quest for a sustainable society is because it is engineers who will devise the actual products, processes and projects that will be required to transform society during the present century. This is a huge challenge, but one which is familiar to engineers and therefore probably not as challenging as the preceding goal; that of changing mindsets. Once the initial goal is achieved, things can change very rapidly as individuals within society become team players towards creating a sustainable society (RAE, 2006) while it will be possible, and probably necessary, to place appropriate R&D spending *"on a wartime footing"* (Prins and Rayner, 2007). In this new context chemical engineers, along with colleagues in other branches of engineering and science, will have the expertise as well as the motivation to ensure that the rest will follow.

Thirdly, and most importantly, chemical engineers have an ethical responsibility to help create a sustainable society; and this responsibility extends beyond the mere technological development of processes and products; because of their unique understanding and insights into the nature of the physical world and the material and energy consuming processes that underpin our society, they have a duty to both share these with other partners and work with them to change hearts and minds towards the new paradigm and to (re)construct such a society.

5.2 Attracting new engineers

There has been a general decline in the relative proportion of students undertaking engineering programmes over the past number of decades in many developed countries (RAE, 2007; NSB, 2008). This situation has led to some exasperation since, at a time *"when our young people are increasingly interested in how they can help to save the planet, we are failing to persuade them that engineering careers are exciting, well-paid and worthwhile"* (King, 2007). On the other hand, there has been a steep increase in both the number and popularity of sustainable energy, environmental engineering and sustainability related programmes and elective streams/options in recent years on chemical engineering programmes (Byrne, 2006), while there is an increased demand for energy led programmes (Jennings, 2009). In chemical engineering, entry numbers have surged in the UK since 2001 reaching record levels in 2008 (IChemE 2007a & 2008). While chemical engineering graduate numbers have suffered a decline over the same period in the US, enrolment patterns show that this trend will be reversed presently (Rhinehart, 2008). The recent UK upturn has been attributed to the role that chemical engineers *"now, more than at any time in the past"* play in *"meeting the societal needs of energy provision, health care and tackling head-on crucial environmental issues that affect everyone"* (Schaschke, 2007). Certainly this analysis would appear to tally with the needs, motivational drivers and inspirations behind many engineering students who would seek to *"make difference to the world"* (Alpay et al., 2008). A recent British study (RAE & ETB, 2007) found that the potential to effect large scale change to the world in a positive way and the expression of social responsibility i.e. being of benefit to people and society, were the two of the factors with the greatest potential to engage people with engineering. Embracing sustainability is therefore likely to result in increased levels and quality of enrolments to chemical engineering programmes (Clift, 2006), while failure to modify programmes in a timely manner could negatively affect recruitment and ultimately present accreditation difficulties (Desha et al, 2009)

Embedding sustainability into engineering programme curricula also offers the potential to increase the proportion of females in the profession (Conlon, 2008). *"Making a difference to the world"* was shown to be the number one aspiration of female students at a London university, but only featured third among males (Alpay et al., 2008). Additionally, a recent CEP survey showed that an appreciably higher percentage of females (84%F v 70%M) consider that sustainability issues will impact significantly on chemical engineering over the next quarter century (Ziemlewski, 2008) and over 70% of female engineering students felt that sustainable development was important when choosing a programme against 59% of males in a recent British survey (Pelly, 2007). It is also envisaged that if engineering students can see the bigger picture and believe that they can have a positive effect in society, as would be realised through a sustainability embedded programme, this would contribute towards higher levels of student motivation throughout their programme (Alpay et al., 2008). Initiatives to introduce sustainability related courses into existing programmes appear to confirm this hypothesis (Harris and Briscoe-Andrews, 2008).

6. CONCLUSIONS

Sustainability will be the context within which chemical engineering is practiced throughout the 21st Century and beyond. While the professional institutions have shown some lead through various high level initiatives and commitments, it is now imperative that they rapidly move to make the systemic embedding of sustainability a key requirement for programme accreditation. Educators will play a key role in developing sustainability informed curricula and it is therefore imperative that there is buy in regarding the need to incorporate sustainability through chemical engineering practice. Given the substantial issues at hand as a result of our unsustainable societal construct, as well as the limited progress that has been made to date, there is now a strong case for progress on embedding sustainability to be *"significantly accelerated"* (Desha et al, 2009). Achieving such change will require discussion, dialogue and education among educators on matters of sustainability. A renewed curriculum and recalibration of chemical engineering graduates' perception of their roles and responsibilities towards society will help precipitate the societal paradigm change that will occur as a result of the consequences of a global society engaged in continued unsustainable practices. It is the ethical responsibility of chemical engineers, in concert with other engineers, to lead on altering the attitudes of society, given the unique position of chemical engineers in particular, in understanding and applying systems approaches and due to their capacity to design and develop the products and processes that will help realise a sustainable society. Chemical engineers also have a duty to engage and learn from other stakeholders. The result of this will be a shift in self-perception, ethos and role, and a correspondingly greater capacity to influence positive change; the profession therefore can be reinvigorated as it moves centre stage. This will result in an enhanced public profile and image and one which will have increased capacity to attract potential recruits to the profession. The 21st Century, with all its unprecedented, wicked and complex problems emanating from our unsustainable societal construct requires nothing less; it behoves chemical engineers to play a full part in meeting, and indeed leading society in facing the challenges ahead.

REFERENCES

ABET, 2007, *Engineering programs effective for evaluations during the 2008-2009 accreditation cycle,* ABET, Baltimore, Maryland, USA.

Allenby, B.R., Allen, D.T. and Davidson, C.I., 2007, Teaching sustainable engineering, *J Ind Ecol,* 11(1): 8-10.

Allenby, B., Murphy, C.F., Allen, D. and Davidson, C., 2009, Sustainable engineering education in the United States, *Sustain Sci,* 4,7-15.

Alpay, E., Ahearn, A.L. Graham R.H.and Bull A.M.J., 2008, Student enthusiasm for engineering: charting changes in student aspirations and motivation, *Eur J Eng Ed,* 33(5): 573-585.

Anderson, R., 2001, Time for a new industrial revolution. *Keynote address presented at the 2001 South Carolina Environmental Symposium,* Columbia, South Carolina, USA. Url: http://ipspr.sc.edu/ejournal/industrialrev.asp

Arai, K., Smith Jr., R.L. and Aida, T.M., 2009, Decentralized chemical processes with supercritical fluid technology for sustainable society, *J. Supercrit Fluids,* 47, 628-636.

Arbuthnott, K.D., 2009, Education for sustainable development beyond attitude change, *Int J Sus High Educ,* 10(2): 152-163.

Azapagic, A., Perdan, S. and Shallcross, D., 2005, How much do engineering students know about sustainable development? The findings of an international survey and possible implications for the engineering curriculum, *Eur J Eng Ed,* 30(1): 1-19.

Batterham, R.J., 2003, Ten years of sustainability: where do we go from here, *Chem Eng Sci,* 58, 2167-2179.

Bailey, R., & Clarke, R., 1998, The interpretation of weak sustainability measures and their values in a computed general equilibrium model of the world economic, Working paper series 98-14. The University of Birmingham.

Bebbington, J., 2001, Sustainable development: A review of the international development, business and accounting literature, *Account Forum,* 25(2): 128-157.

Bebbington, J. and Gray, R., 2001, An account of sustainability: failure, success and a reconceptualization, *Crit Per Account,* 12, 557-587.

Bebbington, J., Brown, J. and Frame, B., 2007, Accounting technologies and sustainability assessment models, *Ecol Econ,* 61, 224-236.

Beddington, J., 2009, The interrelated issues of climate change and food security, *GovNet Communications' Sustainable Development 09.* London, England. 19 March 2009.

Beder, S., 1998, The new engineer, *MacMillan,* Melbourne, Australia.

Benyus, J.M., 2002, Biomimicry: Innovation inspired by nature, *HarperCollins,* New York, USA.

Benyus, J. and Pauli, G., 2009, Nature's 100 best: World-changing innovations inspired by nature. *Chelsea Green Publishing Company,* White River Junction, Vermont, USA.

Bi, H.T., 2005, Integrating sustainability into chemical and biochemical engineering curricula at UBC, *AIChE Ann. Meeting,* Cincinnati, Ohio, USA, November 2005.

Binswanger, M., 2001, Technological progress and sustainable development: what about the rebound effect? *Ecological Economics,* 36(1): 119-32.

BIS, 2008, Bank for International Settlements 78th Annual Report, *Bank for International Settlements,* Basel, Switzerland.

Bogataj, L.K., 2008, IPCC Fourth Assessment Report - Climate change is real and here! *Pre-COP IPCC workshop.* Warsaw, Poland. 2 October 2008. Url: http://www.ipcc.ch/graphics/presentations.htm

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

Bucciarelli, L.L., 2008, Ethics and engineering education, *Eur J Eng Ed,* 33(2): 141-149.

Byrne, C.M., Allen, S.D., Lobkovsky, E.B. and Coates, G.W., 2004, Alternating copolymerization of limonene oxide and carbon dioxide, *J. Amer. Chem. Soc.* 126(37): 11404-11405.

Byrne, E.P., 2006, The role of specialization in the chemical engineering curriculum, *Educ Chem Eng: Off J Eur Fed Chem Eng: D,* 1(1): 3–15.

Carew, A.L. and Mitchell, C.A., 2006, Metaphors used by some engineering academics in Australia for understanding and explaining sustainability, *Env Ed Res,* 12(2): 217-231.

CCSP, 2008, Abrupt Climate Change. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Clark, P.U., Weaver, A.J. (coordinating lead authors), Brook, E., Cook, E.R., Delworth, T.L. and Steffen, K. (chapter lead authors)]. U.S. Geological Survey, Reston, Virginia, USA.

CETS, 1986, *Engineering infrastructure diagramming and modeling. Engineering education and practice in the United States,* Commission on Engineering and Technical Systems, National Academy Press, Washington, DC, USA.

Chau, K.W., 2007, Incorporation of sustainability concepts into a civil engineering curriculum, *J Prof Iss Eng Ed Pr,* 133(3): 188-191.

Clift, R., 2006, Sustainable development and its implications for chemical engineering. *Chem Eng Sci,* 61, 4179-4187.

Conlon, E., 2008, The new engineer: between employability and social responsibility, *Eur J Eng Ed,* 33(2): 151-159.

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

Davidson, C.I., Matthews, H.S., Hendrickson, C.T., Bridges, M.W., Allenby, B.R., Crittenden, J.C., Chen, Y., Williams, E., Allen, D.T., Murphy, C.F. and Austin, S., 2007, Adding sustainability to the engineer's toolbox: a challenge for engineering educators, *Environ Sci Technol,* 41(14): 4847-4850.

Declaration of Barcelona, 2004, *2nd International Conference on Engineering Education for Sustainable Development.* Barcelona, Spain.

Url: https://www.upc.edu/eesd-observatory/who/declaration-of-barcelona/ declaration-of-barcelona/html2pdf

Descartes, R., 1638, Discourse on method, part 6.

Desha, C.J., Hargroves, K. and Smith, M.H., 2009, Addressing the time lag dilemma in curriculum renewal towards engineering education for sustainable development, *Int J Sus High Educ,* 10(2): 184-199.

Dewberry, E. L. and de Barros, M. Monteiro, 2009, Exploring the need for more radical sustainable innovation: what does it look like and why?, *Int J Sus Eng,* 2(1): 28-39.

Draper, R., 2009, Australia's dry run, *Nat Geog,* 215, 4, 34-59.

Dresner, S, 2002, The principles of sustainability, *Earthscan,* London, England.

Economist, 2005, A home-grown problem, *Economist,* 376(8443): 69.

ECUK, 2008, *The accreditation of higher education programmes UK Standard for Professional Engineering Competence, Engineering Council UK,* London, England.

Url: http://www.engc.org.uk/documents/EC0005_AHEPBrochure_MR.pdf

ECUK, 2009, *Guidance on sustainability for the engineering profession,* Engineering Council UK, London, England. Url: http://www.engc.org.uk/documents/EC0018_SustainabilityGuide.pdf

EESD Observatory, 2008, Status of engineering education for sustainable development in European higher education, *Engineering Education for Sustainable Development Observatory,* Barcelona, Spain.

Url: https://www.upc.edu/eesd-observatory/why/reports/EESD_Observer_2008_.pdf

Elliott, C. and Deasley, P., (2007) Creating systems that work: Principles of engineering systems for the 21st Century, *Royal Academy of Engineering,* London, England.

Url: http://www.raeng.org.uk/education/vps/pdf/RAE_Systems_Report.pdf

Engineers Australia, 2006, Engineers Australia national generic competency standards – stage 1 Competency standard for professional engineers, *Engineers Australia.* Canberra, Australia.

Engineers Australia, 2007, Engineers Australia Sustainability Charter, *Engineers Australia,* Canberra, Australia.

Engineers Canada/Ingénieurs Canada, 2008, Accreditation criteria and procedures/Normes et procédures d'agrément. *Canadian Council of Professional Engineers,* Ottawa, Ontario, Canada.

Engineers Ireland, 2007, Accreditation criteria for engineering education programmes, *Engineers Ireland,* Dublin, Ireland.

European Commission, 2009, Europeans' attitudes towards climate change, Special Eurobarometer 313, *European Commission,* Brussels, Belgium. Url: http://ec.europa.eu/public_opinion/archives/ebs/ebs_300_full_en.pdf

Evans, L. B., Keairns, D.L. Fogler, H.S. Sofranko, J.A.and Cain R., 2008, A new strategic plan catalyzes AIChE, *Chem Eng Prog,* 104(11): 100-109.

Favre, E., Falk, V., Roizard C. and Schaer E., 2008, Trends in chemical engineering education: Process, product and sustainable chemical engineering challenges, *Educ Chem Eng: Off J Eur Fed Chem Eng: D,* 3, 22-27.

Fenner, R.A., Ainger, C.M., Cruickshank H.J. and Guthrie, P.M. 2005, Embedding sustainable development at Cambridge University Engineering Department, *Int. J. Sus. High. Ed.,* 6(3): 229-241.

Fischer, J., Manning, A.D., Steffen, W., Rose, D.B., Daniell, K., Felton, A., Garnett, S., Gilna, B., Heinsohn, R., Lindenmayer, D.B., MacDonald, B., Mills, F., Newell, B., Reid, J., Robin, L., Sherren, K. and Wade A., 2007, Mind the sustainability gap, *Trends Ecol Evol,* 22(12): 621-624.

Frame, B. and Brown, J., 2008, Developing post-normal technologies for sustainability, *Ecol Econ,* 65, 225-241.

Frame, B. and Cavanagh, J. 2009, Experiences of sustainability assessment: An awkward adolescence, *Account Forum, In Press.*

Funtowicz, S.O. and Ravetz, J.R., 1993, Science for the post-normal age, Futures, 25(7): 739-755.

Furlong, A., 2004, Do chemical engineers care about sustainability? *IChemE,* Rugby, England. Url: http://cms.icheme.org/mainwebsite/resources/file/attitudessustainabledevelopment.pdf

Gomes, V.G., Barton, G.W., Petrie, J.G., Romagnoli, J., Holt, P., Abbas, A., Cohen, B., Harris, A.T., Haynes, B.S., Langrish, T.A.G., Orellana, J., See, H.T., Valix M. and White D., 2006, Chemical engineering curriculum renewal. *Educ Chem Eng: Off J Eur Fed Chem Eng: D,* 1, 116–125.

Grassian, V. H., Meyer G., Abruña, H., Ekem Achenie, L., Allison, T., Brunschwig, B., Coates, G. W., Ferry, J., Garcia-Garibay, M., Gardea-Torresdey, J., Grey, C.P., Huchison, J., Li, C.-J.; Liotta, C., Minteer, S., Mueller, K., Ragauskas, A., Roberts, J., Omuwunmi, S., Schmehl, R., Schneider, W., Selloni, A., Stair, P., Stewart, J., Tyson, J., Voelker, B., White, J.M., Wood-Black, F. and Torn, D., 2007, Viewpoint: Chemistry for a sustainable future, *Env Sci Tech,* 41(14): 4840-4846.

Gray, R., 2006, Social, environmental and sustainability reporting and organisational value creation?: Whose value? Whose creation? *Account Audit Accountab J,* 19(6): 793-819.

Gray, R., 2009, Is accounting for sustainability actually accounting for sustainability. ..and how would we know? An exploration of narratives of organisations and the planet. *Account Org Soc, In press.*

Gray, R., Bebbington, J. and McPhail, K., 1994, Teaching ethics in accounting and the ethics of accounting teaching: educating for immorality and a possible case for social and environmental accounting education, *Account Educ,* 3(1): 51-75.

Grayson, L. P., 1993, *The making of an engineer,* Wiley, New York, USA.

Gutierrez-Martin F. and Hűttenhain, S.H., 2003, Environmental education: new paradigms and engineering syllabus. *J Clean Prod,* 11, 247-251.

Hargroves, K. and Smith, M.H., 2006, *The natural advantage of nations,* Earthscan, Virginia, USA.

Harris, A.T. and Briscoe-Andrews S., 2008, Development of a problem-based learning elective in “green engineering”, *Educ Chem Eng: Off J Eur Fed Chem Eng: D,* 3, 15-21.

Hayles, C.S. and Holdsworth, S.E., 2008, Curriculum change for sustainability, *J Educ Built Environ,* 3(1): 25-48.

Hazelton, P., Malone, M., and Gardner, A., 2009, A multicultural, multidisciplinary short course to introduce recently graduated engineers to the global nature of professional practice, *Eur J Eng Ed,* 34(3): 281-290.

Healy, S., 1999, Extended peer communities and the ascendance of post-normal politics, *Futures,* 31, 655-669.

Hermanowicz, S. W., 2005, Entropy and energy: toward a definition of physical sustainability, *Water Resources Center Archives Working Papers,* University of California Multi-Campus Research Unit.

Url: http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1048&context=wrca

Ho M-W. and Ulanowicz, R., 2005, Sustainable systems as organisms?, *Biosystems,* 82, 39–51.

Holmberg, J., Svanström, M., Peet, D.-J., Mulder, K., Ferrer-Balas D., and Segalàs J., 2008, Embedding sustainability in higher education through interaction with lecturers: Case studies from three European technical universities, *Eur J Eng Ed,* 33(3): 271-282.

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

IChemE, 2001, The sustainability metrics: Sustainable development progress metrics recommended for use in the process industries, *Institution of Chemical Engineers,* Rugby, England.

IChemE, 2005, Accreditation guide undergraduate study – undergraduate chemical engineering programmes at masters and bachelors level, 2nd Ed, *Institution of Chemical Engineers,* Rugby, England.

IChemE, 2007, A roadmap for 21st century chemical engineering, *Institution of Chemical Engineers,* Rugby, England.

IChemE, 2007a, UK Universities celebrate record chemical engineering success, *Institution of Chemical Engineers,* Rugby, England.

Url: http://cms.icheme.org/mainwebsite/general-barafc3d75d.aspx?map=be5ab3a2345c702ff5a33d5afeb80c8f

IChemE, 2008, Driving in the right direction Technical strategy roadmap: Progress report 2008, *Institution of Chemical Engineers,* Rugby, England.

Illge, L. and Schwarze, R., 2009, A matter of opinion - How ecological and neoclassical environmental economists and think about sustainability and economics, *Ecol Econ,* 68, 594-604.

IPCC, 2007, Fourth Assessment Report: Climate Change 2007. *Intergovernmental Panel on Climate Change,* Geneva, Switzerland.

Jennings, P., 2009, New directions in renewable energy education, *Renew Energ,* 34, 435-439.

Kamp, L., 2006, Engineering education in sustainable development at Delft University of Technology, *J Clean Prod,* 14, 928-931.

Kelly, W.E., 2008, General education for civil engineers: Sustainable development, *J Prof Iss Eng Ed Pr,* 134(1): 75-83.

Kilbourne, W.E., Beckmann, S.C. and Thelen, E., 2002, The role of the dominant social paradigm in environmental attitudes: a multinational examination, *Journal of Business Research,* 55(3): 193-204.

King, J., 2007, Introduction, in *Educating engineers for the 21st century,* Royal Academy of Engineering, London, England.

Lohmann, L., 2009, Toward a different debate in environmental accounting: The cases of carbon and cost–benefit. *Account Org Soc,* 34, 499-534.

Loughborough University, 2004, *Toolbox for sustainable design education,* Loughborough University/Higher Education Academy, England. Url: http://www.lboro.ac.uk/research/susdesign/LTSN/Index.htm

Lovelock, J., 2009, *The vanishing face of Gaia: A final warning,* Allen Lane, London, England.

Lundqvist, U. and M. Svanström, 2008, Inventory of content in basic courses in environment and sustainable development at Chalmers University of Technology in Sweden, *Eur J Eng Ed,* 33(3): 355-364.

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

McIsaac, G.E., and Morey, N.C., 1998, Engineers' role in sustainable development: Considering cultural dynamics, *J Prof Iss Eng Ed Pr,* 124(4): 110-118.

Meddings, L. and Thorne, T., 2008, Engineering education project "What I wish I'd learnt at university" - final report, *Forum for the Future Engineers of 21st Century,* London, England.

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

Meyer, J.H.F. and Land, R., 2003, Threshold concepts and troublesome knowledge (1): Linkages to ways of thinking and practising, in *Improving student learning - ten years on,* C. Rust (Ed) (OCSLD, Oxford, England).

Milne, M. J., Kearins, K. N., and Walton, S., 2006, Creating adventures in wonderland? The journey metaphor and environmental sustainability, *Organization,* 13(6): 801–839.

Mitchell, C.A., 2000, Integrating sustainability in chemical engineering practice and education: Concentricity and its consequences, *Trans IChemE Part B,* 78, 237-242.

Mitchell, C.A., Carew, A.L. and Clift, R., 2004, The role of the professional engineer and scientist in sustainable development, in *Sustainable development in practice: Case studies for engineers and scientists* (Azapagic, A., Perdan, S. and Clift, R), Wiley, Chichester, England.

Molle, F., Wester, P. and Hirsch, P., 2009, River basin closure: Processes, implications and responses, *Agr Water Manage, In press.*

Moneva, J.M., Archel, P. and Correa, C., 2006, GRI and the camouflaging of corporate unsustainability, *Account Forum,* 30, 121-137.

Mulder, K., 2004, Engineering education in sustainable development: Sustainability as a tool to open up the windows of engineering institutions, *Bus Strat Env,* 13, 275-285.

Mulder, K., 2006, Engineering curricula in sustainable development. An evaluation of changes at Delft University of Technology, *Eur J Eng Ed,* 31(2): 133-144.

NAE, 2004, The engineer of 2020: visions of engineering in the new century, *National Academy of Engineering,* The National Academies Press, Washington, DC, USA.

Norde, W., 1997, Energy and entropy: a thermodynamic approach to sustainability, *Environmentalist,* 17, 57-62.

NSB, 2008, Science and Engineering Indicators 2008, *National Science Board, NSF,* Arlington, Virginia, USA.

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

O'Connor, M, 2006, The "Four Spheres" framework for sustainability, *Ecol Complex,* 3(2): 285-292.

Oliveira de Paula, G. and Cavalcanti, R.N., 2000, Ethics: essence for sustainability, *J Clean Prod*, 8(2): 109-117.

Pelly, L., 2007, Challenges to engineering education for sustainable development, *Engineering Professors Council (EPC) Annual Congress,* Leeds England, 26-28 March 2007.

Url: http://www.epc.ac.uk/uploads/presentations/Pelly%20-%20EPC%20Congress%2027-28%20March.pdf

Perdan, S., Azapagic, A. and Clift, R., 2000, Teaching sustainable development to engineering students, *Int J Sus High Educ,* 1(3): 267-279.

Perdan, S., 2004, Introduction to sustainable development, in *Sustainable development in practice: Case studies for engineers and scientists,* Azapagic, A., Perdan, S. and Clift, R. (eds), (Wiley, West Sussex, England), pp. 3-28.

Pereira, T., 2009, Sustainability: An Integral Engineering Design Approach, *Renew Sus Energy Rev,* 13, 1133-1137.

Porritt, J., 2007, The critical role of educating future generations to tackle the key challenges in global sustainability, Keynote, *Global sustainability The future for engineering education,* Imperial College London, England, 18 September 2007. Url: http://www.imperial.ac.uk/globalsustainabilityproceedings/

Prins G. and Rayner, S., 2007, Time to ditch Kyoto. *Nature,* 449, 973-975.

Quinn, S., Gaughran, W. and Burke, S., 2009, Environmental sustainability in engineering education - Quo vadis? *Int J Sust Eng,* 2(2): 143-151.

RAE, 2005, Engineering for sustainable development: Guiding principles, *The Royal Academy of Engineering,* London, England.

RAE, 2006, Developing a sustainable energy strategy, *The Royal Academy of Engineering,* London, England.

RAE, 2007, Educating engineers for the 21st century, *The Royal Academy of Engineering,* London, England.

RAE & ETB, 2007, Public attitudes to and perceptions of engineering and engineers, *The Royal Academy of Engineering & the Engineering and Technology Board,* London, England

Rahimifard, S. and Clegg, A.J., 2008, The role of the engineering community in sustainable development, *Int J Sust Eng,* 1(1):1-2.

Rahmstorf, S., 2009, Sea level rise, *The International Scientific Congress on Climate Change, Global Risks, Challenges and Decisions.* Copenhagen, Denmark. 10-12 March 2009. Url: http://climatecongress.ku.dk/

Sustainable Development (1987–2005):

Ravetz, J., 1999, What is post-normal science?, *Futures,* 31, 647-653.

Ravetz, J. and Funtowicz, S., 1999, Post-normal science-an insight now maturing, *Futures,* 31, 641-646.

Ravetz, J., 2006, Post-Normal Science and the complexity of transitions towards sustainability, *Ecol Complex,* 3, 275-284.

Redclift, M., 2005, Sustainable development (1987-2005): An oxymoron comes of age, *Sust Dev,* 13, 212-227.

Rhinehart, R.R., 2008, Tracking trends in undergraduate enrolments, *Chem Eng Prog,* 104(11): 97-99.

Rittel, H. and Webber, M., 1973, Dilemmas in a general theory of planning, *Policy Sci,* 4(2): 155-169.

Ruth, M., 2006, A quest for the economics of sustainability and the sustainability of economics, *Ecol Econ,* 56, 332-342.

Schaschke, C., 2007, in *UK Universities celebrate record chemical engineering success,* IChemE. Rugby, England. Url: http://cms.icheme.org/mainwebsite/general-barafc3d75d.aspx?map=be5ab3a2345c702ff5a33d5afeb80c8f

Segalàs, J., Ferrer-Balas, D. and Mulder, F.K., 2008, Conceptual maps: measuring learning processes of engineering students concerning sustainable development. *Eur J Eng Ed,* 33(3): 297-306.

Smith J.B., Schneider, S.H., Oppenheimer, M., Yohe, G.W., Hare, W., Mastrandrea, M.D., Patwardhan, A., Burton, I., Corfee-Morlot, J., Magadza, C.H.D., Füssel, H.-M., Barrie Pittock, A., Rahman, A., Suarez, A. and van Ypersele, J.-P., 2009, 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

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

Tankersley, J., 2009, California farms, vineyards in peril from warming, U.S. energy secretary warns, *LA Times,* Los Angeles, USA. 4 February, 2009.

Taylor, D.M. and Taylor, G.M., 2005, *Collapse and Transformation,* BEST Futures. British Columbia, Canada.

TCE, 2007, IChemE on Campus; Do you think global warming is related to cyclical sunspot activity and not CO_2 pollution?, *The Chemical Engineer,* 791, 54, May 2007.

TCE, 2009, IChemE on Campus; The UN paints a stark picture of future world water shortages – is this just scaremongering? *The Chemical Engineer,* 815, 15, May 2009.

The Cambridge-MIT Institute, 2006, *The ImpEE project,* University of Cambridge, England. Url: http://www-g.eng.cam.ac.uk/impee/

TNEP, 2004, *The Natural Edge Project,* Griffith University, Queensland, Australia. Url: http://www.naturaledgeproject.net/

Tomkinson, B., Tomkinson, R., Dobson, H. and Engel, C., 2008, Education for sustainable development – an inter-disciplinary pilot module for undergraduate engineers and scientists, *Int J Sust Eng,* 1(1): 69-76.

Tredgold, T., 1828, *Institution of Civil Engineers Charter*, London, England.

Turnpenny, J., Lorenzoni, I. and Jones, M., 2009, Noisy and definitely not normal: responding to wicked issues in the environment, energy and health, Environ Sci Policy, 12, 347-358.

UKERC, 2007, The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency, *United Kingdom Energy Research Centre,* London, England. Url: http://www.ukerc.ac.uk/Downloads/PDF/07/0710ReboundEffect/0710ReboundEffectReport.pdf

Venselaar, J., 2004, Environmental protection; A shifting focus. *Chem Eng Res Des,* 82(12): 1549-1556.

Von Blottnitz, H., 2006, Promoting active learning in sustainable development: experiences from a 4th year chemical engineering course, *J Clean Prod,* 14, 916-923.

Westmoreland, P.R., 2008, Chemical Engineering the next 25 years. *Chem Eng Prog,* 104(11): 31-41.

Woodall, P., 2003, House of cards, *Economist,* 367(8326): s3-5.

Ziemlewski, J. (2008) Where do you think we are headed? *Chem Eng Prog,* 104(11): 43-50.