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Environmental Sustainability and Climate Change Mitigation—CCS technology, better having it than not having it at all!

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Climate change is happening and already manifested in a range of ways, including: global warming, rising sea levels, floods, heat-waves, stronger and more frequent storms, and droughts. One of the major factors in climate change is anthropogenic fossil fuel combustion for energy generation and it is increasing throughout the world. Fossil fuel burning results in carbon emissions. On the basis of the most recent evidence, this article presents some new insights into the carbon dioxide capture and storage (CCS) technology, which can be an environmentally sustainable way to control carbon emissions. The article also focuses on various relevant facts and figures from the literature on CCS technology and explores various challenges that the technology may face in future. © 2011 American Institute of Chemical Engineers Environ Prog, 00: 000–000, 2011

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INTRODUCTION

Currently the most widely accepted climate change scenarios and projections predict annual temperature increases of 1–3.5°C in the forthcoming decades [1–3]. According to the Intergovernmental Panel on Climate Change (IPCC), emissions of greenhouse gases (GHG) will increase the average global temperature by 1.1–6.4°C by the end of 21st century [4]. Over the past few decades, there has been a significant increase in the larger urban areas. Consequent concentration of transportation, industrial infrastructure and buildings, often results in urban heat islands. For example, London, Los Angeles, and Phoenix have all seen average temperature increases of at least 1°C in the past few decades [1, 2]. Increasingly, floods, storms, droughts, and extreme temperatures bear down on communities. In 2004, the top 10 disasters in terms of the number of people affected were all weather related. These types of disasters have occurred throughout history but with total damages amounting to US$130 billion from just these ten events, it is clear that the necessary steps to reduce disasters have not yet been taken [5, 6]. As climate change begins to manifest itself in the form of increased frequency and intensity of various hazards, the need for communities to address climate risks is becoming urgent. The coming decades are likely to bring altered precipitation patterns which might make floods and landslides more frequent in some part of the world while others will experience prolonged droughts and wildfires [7, 8].

The above outlines the global picture. Specifically in the UK, by the 2050s it is expected that increases in average summer mean temperatures will have risen by 3.5°C. There will be increases in winter precipitation of up to 20%, and there will be more frequent severe storms [1, 9–11]. Thus, climate change adaptation and mitigation interventions need to be planned to support the quality of life and well-being of UK citizens. Failure to act now will only mean that costs of tackling climate change will be much higher in the future [12]. The UK will also miss out on the commercial opportunities that will emerge on the pathway to a low carbon economy [12]. The energy that generally comes from fossil fuel combustion subsequently emits unwanted carbon dioxide into the atmosphere. This is one of the major contributory factors and needs to be substantially addressed as a kind of mitigation to climate change. The situation in many other countries is much the same. Thus, there is a growing need for long-term investment [10].

Aims and Objectives

The purpose of the article is to establish the potential of carbon dioxide capture and storage (CCS) technology, particularly in the context of a contribution to environmental sustainability. The article will achieve this objective by assessing the advantages of the technology against the disadvantages and challenges. The article draws together environmental, legislative, social, financial, and economic perspectives from national and European scales to international and global levels. It presents a detailed discussion with novel insights, in such a format that it can be of interest to a diverse audience with different levels of knowledge about the subject. It can therefore, stimulate further debate and research from academe, industry and other sectors such as legislators and regulators. The article also briefly outlines fossil fuel combustion, the greenhouse effect and CCS technology to refresh their definitions as a quick reference. The main novelty of the paper is that it assembles available evidence, regarding CCS into a coherent proposition.

Developed and Developing Countries

CO_2 emissions are currently at their greatest throughout the industrialized countries, although estimates suggest that developing countries will increasingly contribute to global warming in the coming decades. For instance in the UK, targets set for greenhouse gas emissions by many of Britain's largest companies are insufficient to meet UK's 2020 commitments on climate change. Lack of ambition by companies is actually threatening government plans [13, 14]. In the United States, CO_2 emissions per capita equal 20.1 tonnes of carbon, almost twice those of countries such as China and Brazil, 16 times higher than India and 50 times higher than Nigeria and Sudan. If highly populated developing countries follow the same unsustainable production and consumption path as developed countries, the negative consequences will be significant. The challenge is to determine how industrialized countries can manage their environmental impacts, while developing countries can achieve economic growth in a sustainable way [15]. Figure 1 shows the carbon emissions for
F1 various countries around the world.

Global/International Perspective

Globally, predicted increases in energy demands and continued reliance on fossil fuels suggest related CO_2 emissions will have increased by 62% from 2011 to 2030. Two thirds of this growth is expected to be from developing countries, especially India and China [16]. In India alone GHG emissions rose by 58% between 1994 and 2007 with the energy sector contributing over half of the emissions, rendering India the world's fifth largest emitter—after China, the US, Europe and Russia. India's emissions alone are up from 1.2 billion tonnes of carbon dioxide in 1994 to 1.7 billion tonnes in 2007. According to the latest inventory, India relies on coal for 90% of its electricity, which accounts for more than a third of the country's emissions [17, 18]. Similarly, coal is likely to be the preferred fuel for power generation in other developing countries. The increased demand in developing countries will require many new plants which will operate for 40–60 years, strongly influencing future CO_2 emissions. In developing countries, it is not currently economic to include CCS in new plants. However, building "capture ready" plants (so that the CCS technology can be easily added in the future) could be encouraged. Several developing countries, including India and China, are already engaging with CCS through the Carbon Sequestration Leadership Forum [16].

European Perspective and Global Implications

Objectives for the reduction of carbon emissions and environmental protection are not only pursued by national governments. For instance, climate and energy objectives in the European Union include a reduction of 20% in GHG emissions by 2020, and a 20% in energy savings by the same year. The EU has been arguing for some time that it should go further than its current commitment to cut emissions, in particular if international partners increase their ambition. In fact, the EU offered to increase its commitment to a 30% reduction, as part of a genuine global effort [19, 20]. However, the EU has abandoned the 30% reduction target [20]. Many scientists and pressures groups are now calling for 40% reductions [21, 10]. According to the IPCC, global GHG emissions must be reduced by 50% to 80% by 2050, to avoid dramatic consequences of global warming [22]. The difference between 20% and 80% reductions becomes even more of a challenge when it is realised that the demand for energy continues to escalate. On the basis of current trends, the global energy demand is expected to increase by 50% from 2011 to 2030 [22].

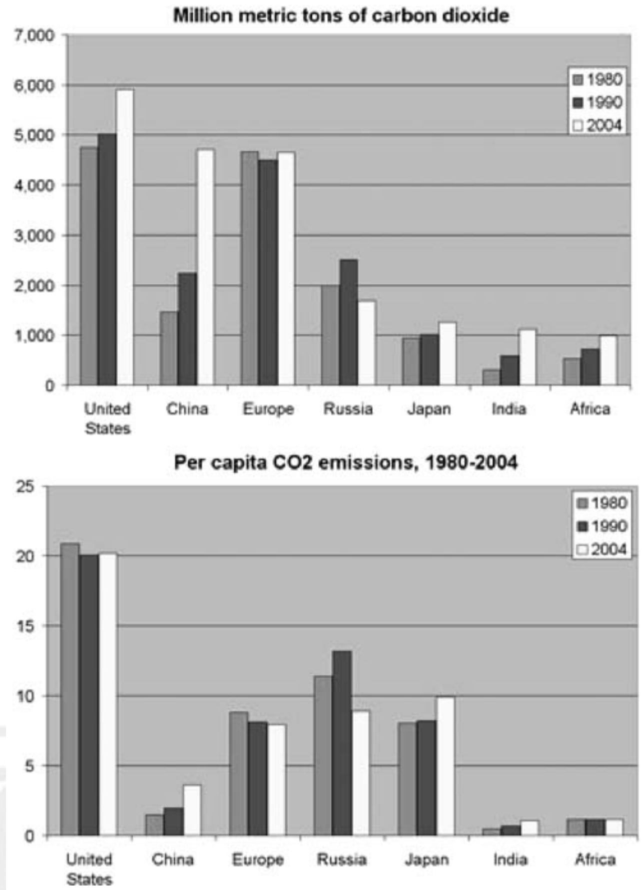

Figure 1. Graphical presentation of carbon emissions of various countries (69). [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

National Perspective—UK

The UK is not an innocent bystander, as the demand for energy in this country has increased by 24% since 1990 and is predicted to grow by 53%, from 2011 to 2030 [23, 24]. The Department of Energy and Climate Change (DECC) has tried to militate against this seemingly insatiable demand, by introducing the Energy Act 2008, the Climate Change Act 2008 and the Energy Act 2010. Other recent Acts of Parliament also cover energy issues, including the Planning Act 2008 (which is of considerable importance for energy infrastructure projects) and the Planning and Energy Act 2008 [25]. Furthermore, the Building Regulations, which are statutory instruments under the Building Act 1984, demonstrate additional requirements for reducing energy use with each revised edition. These provisions apply to existing as well as new buildings whether domestic, commercial or industrial; and specifically address energy efficiency [26]. The new legislation not only covers the consumption and distribution of energy, but also its generation. The aim is to direct the UK towards a philosophy of an energy conscious built environment through reduced carbon emissions, climate change mitigation and adaptation, renewable energy use, and efficient energy consumption. Governments, particularly in various developed countries, such as the UK, are pressing for environmental protection and enhancement. For instance, in 2010, the new UK coalition government contained no fewer than 20 environmental commitments in its manifesto, nearly twice as many as in any other area. The agreement pays particular attention to a low-carbon economy including tougher rules on coal-fired power stations [18].

Table 1. Showing how carbon cut targets in the UK are becoming stringent by the day.

Source	Target versus year			
	Short-term Target	Year	Long-term Target	Year
Energy White paper, DTI, 2003			60%	2050
Energy White paper, DTI, 2007	26–32%	2020	60%	2050
Climate Change Act, 2008	34%	2020	80%	2050
UK Green Building Council	50%	2020		

Unfortunately, the required energy related improvements have not yet picked up pace. For instance, like a number of developed countries, the UK over relies on coal, oil and gas for energy production [27]. The Sustainable Development Commission (SDC) has stated that the government recently reported a 6.3% decrease in carbon emissions from its offices since 1999–2000, which is insufficient to meet the target of 12.5% reduction by 2011–2012. Progress to date is also grossly inadequate in terms of the legally binding national goal to cut emissions by 80% over the 50 years to 2050 [28]. While there is a long way to go and time is becoming shorter, targets for carbon reduction are becoming ever more
T1 stringent as follows (and summarized in Table 1). As part of government's global strategy to address climate change, the 2003 Energy White Paper set the target of a 60% reduction in UK emissions of GHG by 2050 [16, 29]. The Energy White Paper 2007 states that carbon emissions need to be cut by 26–32% up to 2020 and 60% by 2050 to meet the energy challenge, without the further construction of any nuclear power stations [30]. In addition, the Climate Act 2008 legally binds the UK to at least a 34% reduction by 2020 and 80% by 2050 [31]. Although not legally binding, the UK Green Building Council has raised the game by insisting that the UK needs to reduce carbon emissions by 50% up to 2020 [21]. In ac-
T2 cordance with the Climate Change Act, Table 2 shows intermediate UK targets in steps of 5 years up to 2022 [32]. Attempting to meet these increasingly demanding targets through only renewable energy and energy efficiency is not feasible. More could be achieved more if emissions could be controlled at the source of energy production rather than any stage later in distribution and use. This is where Carbon Capture and Storage (CCS) can be applied as a carbon reduction technology applicable at source [33, 34].

COMBUSTION AND CCS

Carbon Dioxide and Greenhouse Effect

Carbon dioxide (CO_2) is produced as a chemical product when combustion, that is an exothermic chemical process, takes place in which fossil fuels (i.e., coal, oil, and gas) are burnt. The largest sources of carbon emissions are cars, lorries, power stations and industrial plants that burn these fossil fuels. Carbon dioxide is a colorless, odorless gas that is also produced when animals (including humans) breathe. Carbon dioxide is essential to the photosynthesis process that sustains plant and animal life. However, carbon dioxide can accumulate in the atmosphere and trap heat near the Earth's surface to cause warming. This is called "the greenhouse effect". Carbon dioxide is the most abundant greenhouse gas [35]. Other greenhouse gases include methane (CH_4), nitrous oxide (N_2O), hydro-fluoro-carbons (HFCs), perflouro-carbons (PCFs), and sulphur hexafluoride (SF_6) [36]. Nevertheless, the focus of this paper is on carbon dioxide.

The Greenhouse Effect is predominantly attributable to the increasing consumption of fossil fuels, particularly oil and coal, which in turn increases emissions of carbon dioxide (CO_2). Carbon emissions restrict escape of the sun's heat

Table 2. Intermediate targets set in 5 year steps for the period of 2008 to 2022 (HM Government, 2010).

Source	Target	5 year step
Climate Change Act, 2008	22%	2008–2012
	28%	2013–2017
	34%	2018–2022

from the atmosphere thereby giving rise to global warming. Although combustion is a process in which humans have always been engaged, the advent of industrialization multiplied carbon emissions on an expediential scale. Furthermore, even in a post-industrial society, emissions continue to increase not only due to unsustainable energy generation, distribution and consumption but also due to escalation of energy demand [37–40].

Carbon Capture and Storage

Carbon capture and storage (CCS) is a means of mitigating the contribution of fossil fuel emissions to global warming. The CCS process consists of separating and capturing CO_2 from large energy-related sources (such as fossil fuel power plants and various industrial processes), transporting and storing it by different means as listed below:

- Solid storage by reaction of CO_2 with metal oxides to produce stable carbonates;
- Liquid storage in the ocean; and
- Gaseous storage in various deep geological formations/settings (for example, in used oil and gas fields, aquifers, etc.)

CCS can also be termed the scrubbing of CO_2 from ambient air by a geo-engineering technique. The act of carbon dioxide capture and storage has also been used in the analysis of biological techniques such as biochar burial, which use trees, plankton, etc. to capture CO_2 from the air. However, it is more appropriate in the nonbiological processes of capturing carbon dioxide from combustion at source [16, 38, 40–42].

The capture of carbon dioxide can take place either after combustion or following the processing of the fuel before combustion. The former is called Post-combustion Capture and the latter, Pre-combustion Capture. In addition to the carbon capture aspect, nitrogen can be removed from flue gases after combustion, and from air before combustion. Depending on the circumstances, CCS technology comes in different types, such as oxy-fuel combustion and chemical looping combustion. The process of oxy-fuel combustion involves burning fossil fuels in pure oxygen as opposed to air, generating a more complete combustion. This results in an exhaust stream that includes water vapor, but this can be easily separated from the carbon dioxide (CO_2) by condensation. However, the main problem with this method is separating oxygen from air. With the Chemical looping type, oxygen is transferred from the combustion air to the gaseous fuel by means of an oxygen carrier. The fuel and combustion air are never mixed, and the gases from the oxidation of the fuel, i.e. CO_2 and H_2O, leave the system as separate streams [43–48].

PROS AND CONS OF CCS

According to IPCC, Carbon Capture and Storage has the potential to mitigate one-third of carbon emissions and could be used at 7000 industrial facilities worldwide by 2050 (including thermal power plants, steel plants, cement factories, refineries, and petrochemical plants). It could also offer a significant improvement in the responsible production of sour gas and extra-heavy oil. The major components of a CCS system include capture (separation plus compression), transport, and storage (including measurement, monitoring, and verification). In one form or another, these components are commercially available. However, there is little commercial experience with configuring all of the components into fully integrated CCS systems at the kinds of scales which would likely characterize their future deployment. For instance, the Lacq demonstration project in France has been in operation since January 2010, but It is one of only two in the world to span the entire chain of natural gas extraction, treatment and combustion to carbon collection, transportation and storage (via injection to deep geological layers which in this case is) at a depth of more than 4000 m in a depleted gas field. In two years, this plant is expected to capture and trap 120,000 metric tons of carbon [35, 38, 40, 49, 50]. Yet, there a number of question marks against its replicability.

Benefits and Advantages

CCS can extend the life of power plants and oil refineries that would otherwise be closed due to high levels of emissions. In this way, fossil fuels can continue to play a role within a diverse energy mix. This can create new economic opportunities and reduce costs in dealing with the implications of climate change [51]. For a modern conventional power plant CCS can reduce CO_2 emissions by approximately 80–90% [38]. Moreover, power plants together with industrial installations can reduce carbon emissions by more than 90% [51]. CCS can play a effective role in achieving carbon reduction targets introduced by the Climate Act 2008 in the UK (See Section National perspective – UK for details) and could reduce energy-related carbon dioxide emissions by a third between now and 2050 [35].

With CCS application, fossil fuel power plants could be more socially acceptable than renewable technologies such as wind farms. These are harmful for bird life [52], create visual intrusion in the landscape as well as generate noise pollution. Also the power supply from wind turbine is not particularly reliable. For example, the proportion of electricity derived from renewable sources such as wind and hydro power in the UK fell by 7.5% in the first three months of 2010 compared with 2009. This reduction in output was due to a dry winter and low wind speeds. Consequently, the UK became a net importer of gas for the first time in more than 40 years [20, 53]. In fact, there are generic barriers to growth in renewable energy generation and efficient energy consumption. Only 13% of global energy demand is met by renewable energy sources. This share will only increase to 16% by 2030. An increased implementation of renewable energy has been slowed down by economic, technical, land-use, social and even environmental issues. The limited potential for renewable energy is a strong indication that energy production from fossil fuels with CO_2 Capture and Storage (CCS) is an important option for reducing global CO_2 emissions and mitigating climate change while energy demands continue to increase [54, 55]. In addition, the difficulties with nuclear energy are well documented. Nuclear waste presents carcinogenic and explosion risks which are serious health and safety issues. Socio-economic issues hinder the building of new nuclear power stations. Setting aside nimbyism issues, Swedish power company Vattenfall has put its participation in the nuclear new-build programme on hold for at least 18 months to focus on renewable energy in the UK. The decision followed the International Energy Agency (IEA) report to the G8 energy ministers in May 2009, which said that the global recession is hindering investment in nuclear power [56].

The EU considers CCS as an important bridging technology that will contribute to mitigating climate change and estimates that CO_2 emissions avoided exclusively through the use of CCS could account for 15% of reductions by 2030 [57]. Thus, despite the science and technology of CCS being in its infancy, there can be no doubting that its adoption is gathering momentum behind EU's determination to stimulate and regulate the uptake of the technology as a key part of its strategy to reduce carbon emissions [58, 59]. CCS has flexibility in application [16, 38, 40] and can be retrofitted to already existing power plants. Thus, it can be applied to both existing and new power plants. The world's oceans already hold 400 billion tons of CO_2 from fossil fuel consumption. Consequently, their acidity has already increased by 0.1pH units. This means that nutrients for plankton in all shallow ocean water, as well as the North Sea, are diminishing rapidly. This is the base of the food chain for invertebrates, shells and, eventually, economic fishing. By 2050 the ocean will become 5 times more acidic than at any time since glaciations [37, 39]. Thus, CCS can help to control this environmental degredation.

Mines in sedimentary rocks may offer some CO_2 storage opportunities, e.g. potash and salt mines or stratabound lead and zinc deposits [38]. Abandoned coal mines in particular, offer an opportunity to store CO_2, with the added benefit of absorption into the remaining coal deposits [41, 38]. Similarly, depleting oil and gas fields can be another means of CO_2 storage [16]. CCS becomes an even more important technology to be researched, developed and deployed as the outcome of recent scenario studies indicate that the number of large energy generation sources is projected to increase. By 2050, given expected technical limitations, around 20–40% of global fossil fuel CO_2 emissions could be technically suitable for capture, including 30–60% of the CO_2 emissions from electricity generation and 30–40% of those from industry [38].

Challenges and Disadvantages

CO_2 is captured as a gas. Therefore, for transportation, it needs to be compressed and cooled, which requires energy input. Bulk transportation can be undertaken by tanker or pipeline. Tankers can be used in smaller projects but for larger volumes, pipelines are the only practical option. CO_2 distribution by pipeline is an established commercial technology. Over 3000km of pipelines are currently used for several million tons of CO_2 per year for Enhanced Oil Recovery (EOR) in the US and Canada. To address the issue of a decrease in net CO_2 emissions in a CCS process, 10–40% more energy is needed by a power plant to capture and compress CO_2 [38]. On the other hand, some 25% of the UK's demand for heat could be met if Combined Heat and Power (CHP) were to be used in power stations [60]. This means that the 10–40% energy increase could be off-set by the 25% decrease from using CHP. To be useful in climate change mitigation, it may be necessary to store the CO_2 for hundreds of years until well past the end of fossil fuel era [16]. However, further research which is underway can make safety of storage more reliable [54, 61]. The gas disasters at Lake Monoun in 1984 and Lake Nyos in 1986, both situated in Cameroon, claimed 37 and 1746 human lives, respectively, as well as the livestock that died due to asphyxiation. These incidents were caused by large amounts of CO_2 stored in these lakes suddenly belching out. However, these two lakes are natural places in close proximity to each other. Furthermore, the depth of CO_2 storage is no more than 200 m in both cases, which in geological CO_2 storage terms is not a safe depth. Also, as the lakes do not have depths similar to the oceans, they do not exert as much pressure on the CO_2 gas once it has leaked from the geological bottom. Therefore, when the storage in the lakes reaches a certain pressure, the CO_2 can be belched out in large amounts. An industrial degassing system for the lakes has been devised to render the two situations safe [62–65]. Although these are natural and unusual cases, but they do raise concerns if CO_2 is stored in deep geological formations, as there is a risk of leakage into the atmosphere. The ability of geological structures to retain CO_2 over hundreds or thousands of years without leaking is therefore an issue. Technology for CO_2 storage in coal seams is at an early stage. However, there is a growing understanding of storage in oil and gas fields and saline aquifers. For example, the oil and gas fields and aquifers in the North Sea sector of the UK have large storage potential estimated to be approximately 20,000–260,000 million tons [16]. As Innset [54] points out, even if leakage happens it would be at a slower rate. Thus, it is still better to stop carbon emissions entering the atmosphere by storing the captured CO_2 in deep geological structures where there are no human populations in the vicinity, even if there is a small risk of a leak. If it is stored in deep ocean masses, there is a risk of leakage and subsequent increasing acidity in the water. There are uncertainties about how long CO_2 injected into the deep ocean will remain there and the potential impact on marine ecosystems. This aspect needs further research and development [16, 38]. Moreover, the oceans are already becoming acidic due to CO_2 emissions into the atmosphere [37, 39].

In terms of financial viability, particularly where the CCS technology is predominantly at demonstration stage, it is not likely that industry will invest in the deployment of CCS, even for EOR; and current market conditions do not help. CCS might become more viable under schemes where value is attached to CO_2 emission reduction. To be included in such schemes, an acceptable methodology for carbon accounting in terms of CCS needs to be developed [16]. It is expected that in the near future technology will move on from the demonstration stage to full scale application. In the context of new legislation on emissions, this may encourage investment [51, 39]. For example, the EU plans to fund up to four CCS projects in the UK together with a new framework for coal and CCS [39, 66]. Similarly, The Energy Technologies Institute (ETI) has launched £25 million for research into carbon capture [67]. Facilitating the distribution of the technology to developing countries would be a major issue for the adoption of CCS worldwide. Furthermore, technology transfer faces several barriers, including intellectual property rights and access to capital. In addition, since it will rely on the development and integration of technologies, some of which are not yet used for such purposes, there is considerable scope for trial and error. [38]. Literature regarding CCS reports a fairly wide range of costs for employing the systems with fossil-fired power production and various industrial processes. The range of these cost estimates is driven primarily by site-specific considerations such as the technology characteristics of the power plant or industrial facility; the specific characteristics of the storage site; need for knowledge enhancement of the technology; and the required transportation distance of the CO_2. Moreover, estimates of the future performance of components for the capture, transport, storage, measurement and monitoring systems are uncertain due to lack of experience. However, the literature also reflects a widely held belief that the cost of building and operating CO_2 capture systems will fall over time as a result of technological advances [38, 68]. Irrespective of whether existing and retrofitted with CCS or new build plants with CCS integrated at the outset, the general understanding is that the cost of energy from power plants will increase. Yet, there are industry reports suggesting that with successful research, development and deployment (RD&D), sequestered coal-based electricity generation in 2025 will be less than unsequestered coal-based electricity generation today [61, 68].

All the challenges noted above can be dealt with not only by establishing an integrated network of economic incentives and further research and development; but also in the short term by different combinations of the various attributes noted above. According to the sustainability philosophy, it is necessary that future generations do not inherit irreversible climate change impacts and a planet with carbon emissions beyond remediable limits, even if it involves significant expenditure.

CONCLUDING REMARKS

If CO_2 emissions were to be considered as withdrawals from the Bank of Climate Stability, since the industrial revolution the climate debt has been increasing [13]. The level of climate debt is now so high that we are on the verge of a global disaster. To continue the metaphor, it will be many years before the loans could be paid back (which would actually require a net removal of CO_2 from the atmosphere every year), and there is an urgent need to reduce the quantity of borrowing. For industrialized countries the Intergovernmental Panel on Climate Change (IPCC) notes that to prevent dangerous climate change, annual withdrawals need to be reduced to 20% of the 1990 level. If the reduction in emissions follows a fixed percentage every year then it should be about 4% per annum on a compound basis between 2009 and 2050 [13].

According to the IPCC, global greenhouse gas (GHG) emissions must be reduced by 50–80%, by 2050 to avoid the dramatic consequences of global warming. Scenarios from the International Energy Agency (IEA) indicate that the potential for reduced CO_2 emissions through enhanced energy efficiency and increased renewable energy production is limited. According to the IPCC, a delay in CO_2 emission reductions can lead to melting glaciers, rising sea levels, coastal floods, etc., and a new strategy for reducing CO_2 emissions is required as soon as possible. Carbon Capture and Storage (CCS) is a technology with potential for large reductions in CO_2 emissions within 10–20 years. Therefore, the strategy for reducing global CO_2 emissions must be a combination of increased energy efficiency, more renewable energy production, and a wide implementation of CCS. By establishing stronger incentives favoring ambitious but realistic renewable energy and energy efficiency proposals, and by ensuring wide deployment of full CCS potential—global CO_2 emissions can be reduced by $\sim$70% by 2050 (i.e., the IPCC target); although this requires the establishment of strong regulatory and economic incentives to realize the full potential for energy efficiency, renewable energy and CCS [33].

With reference to the famous proverb, "prevention is better than cure," the same applies to the issue of climate mitigation, which is better than climate change adaptation. The former is proactive and latter is reactive. Already climate change is happening and accelerating, therefore adaptation has already become compulsory. Yet it is a question of whether to continue relying on adaptation while compromising mitigation, or take-up mitigation measures in a pro-active way. Therefore, from the economic perspective, even though CCS application could add costs onto energy bills, it may be preferable to pay a little more now, than substantially more later, when adaptation costs of climate change impacts could be much higher. To tackle additional costs, subsidies might be paid to deprived or less privileged parts of society and small businesses.

From environmental perspective, CCS has considerable potential to shrink ecological or carbon footprints of energy not only at local, regional, national or continental scale but also at the global level. Thus, CCS can contribute to climate change mitigation from the microscopic to macroscopic. Carbon emissions into the atmosphere are also reducing air quality. Thus, CCS is an effective tool for human health as well as environmental protection, although leakage risks from CO_2 storage needs to be further researched.

On the basis of the above discussion, an overall view can be safely drawn that CCS is a productive way forward to meet the accelerating need for reduction in carbon emissions. This will consequently help to curtail the anthropogenic part of global warming. If benefits are compared with challenges, it is clear that the challenges are not insurmountable. These challenges can be overcome with further research and development to combat any likely hazards and risks of the technology, and socio-economically, with well established incentives and frameworks. Furthermore, CO_2 emissions into the atmosphere are increasing acidity in the oceans, as well as contributing to lower air quality, escalating the green house effect resulting in global warming, melting glaciers and raising sea levels. When compared with initial expenditure and the risk of leakage, the conclusion from the bigger picture is that having CCS technology is better than not having it at all. Based on the above discussion of social, economic and environmental aspects, it is evident that CCS can also contribute to the wider agenda of sustainable development for both current and future generations.

LITERATURE CITED

1. Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., & Hill, S. (2002). Climate change scenarios for the United Kingdom: The UKCIP 2002 Scientific Report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK, p. 120.
2. Crawley, D.B. (2008). Estimating the impacts of climate change and urbanization on building performance, Building Performance Simulation, 1, 91–115.
3. Crawley, D.B. (2003). Impact of climate change on buildings, Proceedings of the CIBSE/ASHRAE International Conference 2003, Edinburgh, Scotland, London: CIBSE.
4. IPCC (Intergovernmental Panel on Climate Change), Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, & H.L. Miller (Eds.), Cambridge, United Kingdom and New York, NY: Cambridge University Press, 2007.
5. CRED (Centre for Research on the Epidemiology of Disasters). (2005). 2005 disasters in numbers, Top 10 countries, Available at: **http://www.unisdr.org/disaster-statistics/pdf/2005-disaster-in-number.pdf**, Accessed on March 2010.
6. CRED (Centre for Research on the Epidemiology of Disasters). (2005). International Strategy for Disaster Reduction, Disaster Statistics - Top 50 countries, Available at: **http://www.unisdr.org/disaster-statistics/pdf/isdr-disaster-statistics-50top-countries-pdf**, Accessed on March 2010.
7. IPCC (Intergovernmental Panel on Climate Change). (2001). Climate change 2001: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK: Cambridge University Press.
8. IATF (Inter-Agency Task Force on Climate Change and Disaster Risk Reduction). Disaster risk reduction tools and methods for climate change adaptation, Available at: **www.unisdr.org/eng/risk-reduction/climate-change/docs/DDR-tools-CCA-UNFCC.pdf**, IATF Working Group on Climate Change and Disaster Risk Reduction, Accessed on March 2010.
9. ODPM (Office of the Deputy Prime Minister). (2006). Planning Policy Statement 25: Development and flood risk, ODPM.
10. Butt, T.E., Giddings, B., Cooper, J.C., Umeadi, B.B.N., & Jones, K.G. (2010). Advent of climate change and energy related obsolescence in the built environment, In International Conference on Sustainability in Energy and Buildings, Brighton, UK, 5–7 May.
11. Butt, T.E., Umeadi, B.B.N., & Jones, K.G. (2010). Sustainable development and climate change induced obsolescence in the built environment, In International Sustainable Development Research Conference, Hong Kong, China.
12. CBI (Confederation of British Industry). (2007). Climate change: Everyone's business, CBI.
13. CDP (Carbon Disclosure Project). (2009). The Carbon Chasm—Based on Carbon Disclosure Project 2008 responses from the world's 100 largest companies, CDP.
14. IEMA (Institute of Environmental Management & Assessment). (2010). Greenhouse gas targets falling short, says CDP, The Environmentalist, Issue 90, p. 3, 18 January.
15. UNEP (United Nations Environment Programme). (2007). Buildings and climate change: Status, challenges and opportunities, UNEP.
16. POST (Parliamentary Office of Science and Technology). (2005). Carbon capture and storage (CCS), Postnote, Number 238, Parliamentary Copyright, March.
17. Guardian. (2010). India's greenhouse gas emissions rise by 58%—Energy sector responsible for over half of India's rise in emissions, says a new government report.guardian.co.uk/environment/2010/may/1/India-greenhouse-gas-emissions-rise, Accessed on July 2010, Guardian, Accessed on Wednesday, 12 May.
18. IEMA (Institute of Environmental Management & Assessment). (2010). Do blue and yellow make a green coalition? The Environmentalist, Issue 99, p. 2, 1 June.
19. EC (European Commission). (2010). Communication from the Commission to the European Parliament, the European Economic and Social Committee and the Committee of the regions, COM (2010) 265, Available at: **http://ec.europa.eu/environment/climat/pdf/2010.05–26communication.pdf**, Accessed on July 2010, Brussels, 26 May.
20. IEMA (Institute of Environmental Management & Assessment). (2010). EU abandons 30 percent reduction target—for now. The Environmentalist, Issue 101, p. 8, 5 July.
21. RUDI Ltd., Built environment carbon emissions should be cut by 50% by 2020, challenges green body, Available at: **http://www.rudi.net/node/21688**, Accessed on April 2010.
22. Stangeland, A. (2007). Why CO_2 capture and storage (CCS) is an important strategy to reduce global CO_2 emissions, Bellona Position Paper, Available at: **http://www.bellona.org/articles/articles_2007**, Accessed on July 2010, The Bellona Foundation.

23. DTI (Department of Trade and Industry). Energy—Its impacts on environment and society—Chapter 3, Available at: **http://www.dti.gov.uk/files/file20300.pdf**, Accessed on May 2010.
24. BIFM (British Institute of Facilities Management). (2007). Position paper: energy, executive summary, BIFM, 10 January.
25. DECC (Department of Energy and Climate Change). (2010). Legislation, Available at: **http://www.decc.gov.uk/content/cms/legislation/legislation.aspx**, Accessed on April.
26. DCLG (Communities and Local Government). Planning, building and the environment - Building regulations, Available at: **http://www.communities.gov.uk/planningandbuilding/buildingregulations/**, Accessed on April 2010.
27. Hart, J. (2010). Photovoltaic installations in the domestic sector: A model of the environmental and economic implications of the proposed UK feed-in tariff scheme, The Environmentalist, Issue 101, p. 8, 5 July.
28. Guardian. (2009). UK government missing own carbon cut targets, Available at: **http://www.guardian.co.uk/environment/2009/may/01/government-failing-emissions-targets**, 01 May.
29. DTI (Department of Trade Industry). (2003). Our energy future, DTI White Paper.
30. DTI (Department of Trade and Industry). (2007). Meeting the energy challenge, A White Paper on Energy, HM Government, TSO (The Stationary Office).
31. DECC (Department of Energy and Climate Change). (2010), Climate Change Act 2008, Available at: **http://www.decc.gov.uk/en/content/cms/legislation/cc_act_08/cc_act_08.aspx**, Accessed on April.
32. HM Government. (2010). Climate change: Taking action, delivering the low carbon transition plan and preparing for a changing climate, Crown Copyright.
33. Stangeland, A. (2007). Cabron capture and storage (CCS) should be implemented in the CDM mechanism, Available at: **http://www.bellona.org/articles/articles_2007**, Accessed on July 2010, The Bellona Foundation.
34. Stangeland, A. (2007). CO_2 capture and storage—Why is it so important? Available at: **http://www.bellona. org/articles/articles_2007**, Accessed on July 2010, The Bellona Foundation.
35. Total. (2009). Ten Questions for Total - Environment and Society Report 2009, Total.
36. HTC Purenergy. Glossary of Industry Terms, Glossary of Terms - CO_2, HTC Purenergy, 2009, Available at: **http://www.htcenergy.com/mediaCenter/glossary_CO2.htm**, Accessed on January 2011.
37. Caldeira, K., & Wickett, M.E. (2003). Oceanography: Anthropogenic carbon and ocean pH, Nature, 425, 365.
38. IPCC (Intergovernmental Panel on Climate Change). (2005). Carbon dioxide capture and storage. In B. Metz, D. Davidson, H.C. Coninck, M. Loos, & L.A. Meyer (Eds.). The IPCC Special Report, Prepared by working group III of the Intergovernmental Panel on Climate Change, Cambridge University Press.
39. Haszeldine, S. (2009). Carbon Capture and Storage, Available at: **http://www.co2storage.org.uk/**, CSC UK and University of Edinburgh.
40. Total. (2010). Energies No. 17 - France, here and there, Total.
41. Piessens, K., & Dusar, M. (2004). Feasibility of CO_2 sequestration in abandoned coal mines in Belgium, Geologica Belgica, 7, 3–4.
42. Saether, A.K. (2009). Bellona report calls for legislation on carbon capture and storage, Available at: **http://www.bellona.org/articles/articles_2009**, Accessed on July 2010, The Bellona Foundation.
43. Lyngfelt, A., Leckner, B., & Mattisson, T. (2001). A fluidized-bed combustion process with inherent CO2 separation, application of chemical-looping combustion, Chemical Engineering Science, 56, 3101–3113.
44. Cho, P., Mattisson, T., & Lyngfelt, A. (2004). Comparison of iron-, nickel-, copper- and manganese-based oxygen carriers for chemical-looping combustion, Fuel, 83, 1215–1225.
45. Buhre, B.J.P., Elliott, L.K., Sheng, C.D., Gupta, R.P., & Wall, T.F. (2005). Oxy-fuel combustion technology for coal-fired power generation, Progress in Energy and Combustion Science, 31, 283–307.
46. Tan, Y., Croiset, E., Douglas, M.A., & Thambimuthu, K.V. (2006). Combustion characteristics of coal in a mixture of oxygen and recycled flue gas, Fuel, 85, 507–512.
47. Syamlal, M., Richards, G., & Plasynski, S. (2008). Carbon sequestration - Oxy-fuel combustion, R&D facts, R&D127.indd, National Energy Technology Laboratory (NETOL), US Department of Energy (DoE) Office of Fossil Energy.
48. SCCS (Scottish Carbon Capture & Storage), Containment solutions to complement emissions reduction strategies - Oxy-Fuel Combustion Capture, Available at: **http://www.geos.ed.ac.uk/sccs/capture/oxyfuel.html**, Last modified 20 March 2010, Accessed on January 2011.
49. Total. (2010). Total Tackles Climate Change with the Inauguration of a Carbon Capture and Storage Demonstration Facility, Available at: **http://www.total.com/en/press/press-releases/consultation-200524.html&idActu=2265**, Press release, 11 January.
50. Total. (2009). Factbook 2009, Total.
51. DECC (Department of Energy & Climate Change). (2009a). Government Response to the House of Commons Environmental Audit Committee Report: Carbon capture and storage (CCS), Ninth Report of Session 2007–2008, Crown Copyright.
52. EC (European Community). (1992). Directive on the conservation of natural habitats and of wild fauna and flora (the Habitats Directive), 92/43/EEC.
53. Jowit, J. (2010). Green setback for UK as British power supplied by renewable sources falls, The Guardian, Available at: **http://www.businessgreen.com/business-green/news/2265602/green-setback-uk-british-power**.
54. Innset, O.B. (2009). Safe CO_2 storage is possible, Available at: **http://www.bellona.org/articles/articles_2009**, Accessed on July 2010, The Bellona Foundation.
55. Stangeland, A. (2007). Potential and barriers for renewable energy, Available at: **http://www.bellona.org/articles/articles_2007**, Accessed on July 2010, The Bellona Foundation.
56. PE (Professional Engineering). (2009). Vattenfall pulls back from UK nuclear power programme, PE, 22, 7.
57. Silbert, T. (2010). EU focuses on carbon capture and storage, Newsstand, Available at: **http://www.klgates.com**, 30 September 2009, Accessed on February.
58. Saether, A.K. (2008). International Energy Agency asks the world put its bets on CCS technologies, Available at: **http://www.bellona.org/articles/articles_2008**, Accessed on July 2010, The Bellona Foundation.
59. Hoff, E. (2008). Coalition urges EU ministers to stimulate CCS, Available at: **http://www.bellona.org/articles/articles_2008**, Accessed on July 2010, The Bellona Foundation.
60. PE (Professional Engineering). (2009). UK must invest in CHP plants, PE, 22, 6.
61. CURC (Coal Utilisation Research Council). (2005). Technology Roadmap, Available at: **http://www.coal.org/road map/index.asp**.

62. Kusakabea, M., Tanyilekeb, G.Z., McCordc, S.A., & Schladowc, S.G. (2000). Recent pH and CO2 profiles at Lakes Nyos and Monoun, Cameroon: implications for the degassing strategy and its numerical simulation, Journal of Volcanology and Geothermal Research, 97, 241–260.
63. Evans, W.C., White, L.D., Tuttle, M.L., Kling, G.W., Tanyileke, G. & Michel, R.L. (1994). Six years of changes at Lake Nyos, Cameroon, yield clues to the past and cautions for the future, Geochemical Journal, 28, 139–162.
64. Freeth, S.J., Kling, G.W., Kusakabe, M., Maley, J., Tchoua, F.M., & Tietze, K. (1990). Conclusions from Lake Nyos disaster, Nature, 348, 201.
65. Sigurdsson, H., Devine, J.D., Tchoua, F.M., Pressor, T.S., Pringle, M.K.W., & Evans, W.C. (1987). Origin of the lethal gas burst from Lake Monoun, Cameroun, Journal of Volcanology and Geothermal Research, 31, 1–16.
66. DECC (Department of Energy & Climate Change). (2009). A Framework for the Development of Clean Coal: consultation document, Available at: **http://decc. gov.uk/en/content/cms/consultations/clean_coal/clean_coal.aspx**, Accessed on 17 June.
67. ETI (The Energy Technologies Institute). ETI launches £25m carbon capture search, The Engineer, Available at: **http://www.theengineer.co.uk/channels/process-engineering/eti-launches**, Accessed on 22 March 2010.
68. Scitizen. Carbon capture and storage is an end-of-pipe dream, Available at: **http://www.scitizen.com/future-energies/**, Scitizen, Accessed on 5 September 2008.
69. Mongabay. CO_2 emissions reductions lag 25% behind 2012 targets India's CO_2 emissions leap 88% since 1990, China 73%, Mongabay, May 8 2007, Available at: **http://news.mongabay.com/2007/0508-world_bank.html**, Accessed on January 2011.