TECHNOLOGY AND CLIMATE CHANGE

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BACKGROUND PAPER 4

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TECHNOLOGY AND CLIMATE CHANGE

OVERVIEW

This background paper was inspired by W. Brian Arthur's book, *The Nature of Technology* (2009a), summarized at the end. A distinction is made between energy technologies, measures to improve energy efficiency, and technologies to improve land and coastal management (Cosier 2008, Nellemann et al. 2009). Without relying entirely on their opinions, two main sources provide a framework for assessing technologies (Jacobson 2009, Goodall 2008).

Other sources assist in classifying descriptions of individual technologies into the three classes. The final section deals with the diffusion of technologies with an emphasis on the least developed countries, reflecting the observation that climate change and the poverty trap are the most urgent pair of issues facing the world (Stern 2009). The section includes descriptions of current trends in biotechnology, technologies exploring alternative ways to industrialized agriculture, and the role of technology in assisting the least developed countries, including Sub-Saharan Africa.[1]

RISING INTEREST IN INNOVATION IN THE SOCIAL SCIENCES

Innovation and new technology was long a neglected research area. One statistical indicator shows that scholarly research contributions were few and far between before 1960: only about 0.04% of all social science titles in the second half of the 1950s included the word "innovation". By 1991-93 the proportion had grown to about 0.2% and it then surged to 0.4% between 2002 and 2006 (Fagerberg and Verspagen 2009).[2] A worldwide web-based survey in 2004-05 of over one thousand social scientists (60% of whom were economists) showed that the prime source of inspiration across the board was Joseph Schumpeter, who has been dead for sixty years and developed his basic theories a century ago. The authors observe (p 220):

"Working in the early days of social science, he combined insights into economics, sociology and history into a highly original approach to the study of long run economic and social change, focusing in particular on the crucial role played by innovation and the factors influencing it. In so doing he distanced himself from the (then) emerging neoclassical strand of economics .. . Schumpeter's life-long advocacy for seeing innovation as the driving force

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[1] Professor John Villadsen read a previous draft of this paper, and the final version benefits from his many comments, especially in the areas of nuclear power, biofuels, and biotechnology. The subject of technology has been the hardest to keep up-to-date during the extended time taken to complete the Florida Keys project. All we can hope is to capture the essential character of what is going on in the multifarious areas of technological development that have potential influence on the rate of climate change.

[2] This may look low but reflects the wide coverage of the source: the Social Sciences Citation Index of Thomson Reuter's *Web of Science*, which compiles the essential data from 2,474 of the world's leading social science journals across 50 disciplines, as well as 3,500 of the world's leading scientific and technical journals. See http://thomsonreuters.com/products_services/science/science_products/a-z/social_sciences_citation_index. The real significance is that the *relative* number of references has increased tenfold in 50 years, and doubled in about 12, and the actual number has mushroomed even more as the total number of journal references itself.

behind economic and social change seemed almost a lost cause at the time of his death in 1950. Instead, the economics literature increasingly came to be dominated by highly mathematized, static, equilibrium exercises of the type that Schumpeter admired but held to carry little promise for improving our knowledge about the sources of long run technological, economic and social change." [3]

The revived interest in innovation and technology among economists and other social scientists is a welcome sign as the threat from climate change escalates. The Swedish Tällberg Foundation exemplifies organizations that advocate new and creative solutions based on humankind's interconnectedness, systemic interdependence and requirements for courageous and honest leadership. Its founder and chairman, Bo Ekman, a former member of the Volvo management team, in anticipation of the COP-15 meeting in Copenhagen in December 2009 joined NASA's James Hansen in drawing attention to the growing scientific consensus that atmospheric CO_2 content should be reduced to 350 ppm. Ekman recognizes this task as "herculean" but the 450 ppm target is rapidly becoming regarded as too risky (Ekman 2008, Hansen 2008, Ackerman et al. 2009, Steffen 2009). Ekman refers to the central role of technology by invoking Brian Arthur's work discussed below (Arthur 2009a):

"Brian Arthur, the brilliant Irish economist, observes in his [then] forthcoming book on the theory of technology that technology brings hope but that trust can only be achieved through our conscious relationship with nature. Trust and hope must be fundamental ingredients in our vision of the future and the redesign of the Kyoto agreement."

TECHNOLOGIES AND TECHNOLOGY POLICY

MESSAGES FROM THE NATURE OF TECHNOLOGY

With our focus on developing alternative future scenarios, four key messages emerge from Brian Arthur's view of the role of innovation and evolving technologies (summarized at the end of this background paper with an addendum on "Arthur's Three Laws"):

1. Technological change is an *endogenous* evolutionary process: every new technology is a combination of parts from preceding technologies, made possible by the constant capture and harnessing of natural phenomena on which the technology depends. It is also a *continuing self-creating* process feeding upon its own evolution.
2. Science and technology co-exist (co-evolve) in a symbiotic relationship. One cannot function properly without the other. Strong science makes for strong technology, and *vice versa*. They may combine to help develop high-tech industries which benefit from increasing returns helping them to become dominant in their markets.

[3] It may be another sign of the times that the respected London-based journal, *The Economist*, launched a new column on business and management, *Schumpeter*, on September 17, 2009. The journal commented in the inaugural column: "Schumpeter's ability to see business straight would be reason enough to name our new business column after him. But this ability rested on a broader philosophy of capitalism. He argued that innovation is at the heart of economic progress. It gives new businesses a chance to replace old ones, but it also dooms those new businesses to fail unless they can keep on innovating (or find a powerful government patron). In his most famous phrase he likened capitalism to a "perennial gale of creative destruction". For Schumpeter the people who kept this gale blowing were entrepreneurs."

3. Inventions (radically novel technologies) are *always* based on a technological base of existing components and functions. The process from prototype invention to major technology and subsequent development of a new technological "domain" is time-consuming and involves complex adaptive interactions with the general economy. Radically inventive new technologies may therefore take decades to make their full impact. Some existing bodies of technology, however, keep "morphing" into new offshoot technologies and new domains in a shorter time frame. Communications and information technology are prominent examples.
4. Technology is mainly seen in physical terms. However, physical technologies interact with a plethora of other ways of fulfilling particular human purposes, such as distribution systems and government institutions. Such "purposed systems" have much in common with physical technologies. The integrated approach to coastal management of which the Florida Keys National Marine Sanctuary forms part exemplifies a purposed system which can be adapted to changing circumstances just as physical technologies can.

SOME CONSEQUENCES

Accepting that dynamically evolving industries enjoy increasing returns, there are good economic reasons why particular high-tech markets become dominated by a single player, whether a country, company, or product ("Arthur's First Law"). This provides incentives for governments to nurture such technologies, while discouraging monopolistic practices.

There are equally good reasons for national governments to develop policies that are strongly supportive of scientific research because of the intimate bond between science and technology; those failing to do so risk losing out to competitors elsewhere.

A strong national science policy giving priority to well-designed and adequately funded secondary and tertiary education systems and research institutions also helps ensure that the science remains sensitive to new technologies and new scientific findings, which could lead to the best utilization of the available natural phenomena as well as the uncovering of new ones needed for further technological evolution.[4]

The continuing technological evolution which keeps bootstrapping itself on to new levels according to Brian Arthur (and Schumpeter) is an integral part of the economic system. The better this endogenous process is known, the more effectively it can be influenced by government policy. This is relevant in relation to climate change, which despite the growing scientific evidence of its importance keeps getting sidelined in the political process.

International cooperation is essential, but as events in 2009 proved, domestic politics in the United States, China, Australia and other countries keeps interfering with the effort to reach international agreement. The propaganda against early action on climate change has been deafening. The outcome at the Conference of the Parties in Copenhagen in December 2009

[4] A school curriculum too strongly biased towards science may be counter-productive. There are indications that a rounded education including visual arts, music, and other creative activities may produce even better results than an education promoting science only. This is a complex subject debated among educationalists the world over, and we can do no more than flag it here. In the United States, the National Assembly of State Arts Agencies provides critical evidence linking study of the arts with general student achievement and success (Ruppert 2006).

(COP 15) was negatively affected by an abundance of political factors at a time when all the scientific evidence points towards a need for greater urgency (Hoegh-Guldberg 2010a). The key political factor was the great recession that hit the world in 2008. As discussed in Hoegh-Guldberg (2010a), the positive effect may be giving incentives a stronger role in a direct approach to the decarbonization of the global energy system, rather than an indirect approach via manipulation of the economy (Prins et al. 2009, p 3).

Formation and progress of ARPA-E

The political waves that were raised in 2009 and their impact on the Copenhagen meeting are fortunately not the only activity that will affect the future. Negotiations on climate change are a continuing process that provides the glue between the annual COP meetings.

Also during 2009 the United States Department of Energy's new agency, the Advanced Research Projects Agency – Energy (ARPA-E), came into being. It is useful to comment on its ambitious aims here, because it helps put the whole climate change-related technology issue into perspective as the story develops below. In its first funding round, ARPA-E allocated a total of $151 million to 37 "transformational R&D" projects (see box). It made its first funding opportunity announcement on April 27 and was flooded with an unexpectedly high number of "concept papers" (3,500) by July. About 300 of these applicants were asked to provide full proposals by the end of August, and the funding was announced on October 26.

Projects funded by ARPA-E, October 2009

Project category	Number*
Energy storage	6.5
Biomass	4.5
Carbon capture	5
Renewable power	4
Direct solar fuels	5
Building efficiency	3
Waste heat capture	2
Vehicle technologies	5
Water	1
Conventional energy	1
* Split categories counted half.	37

Funding of individual projects ranged to below $1 million and averaged just over $4 million. Two projects attracted funding of about $9 million: drilling equipment for geothermal energy and bio-butanol from macroalgae. Although bio-butanol may be more efficiently produced by fermentation in large-scale projects, it was noted that "seaweed is a potentially sustainable *and scalable* [our emphasis] new source of biomass that doesn't require arable land or potable water." Exploring different technologies helps cover a wide range of possibilities both within a nation and between countries at different stages of development.

In another initiative, ARPA-E in August sent out a request for information, or RFI, for public response by September 25.[5] The object was to seek public and stakeholder input into (1) programmatic areas well suited for support by ARPA-E and (2) specific scientific and technological opportunities to overcome the technological roadblocks to developing viable

[5] The RFI letter is shown in full at http://arpa-e.energy.gov/public/rfi.pdf.

transformational technologies relevant to ARPA-E's mission. This would assist the agency in developing potential programs and funding opportunities.

Throughout the letter, it stresses that the responses should emphasize "disruptive new, extremely low-cost approaches to manufacturing high quality products," aimed at "translating cutting-edge scientific discoveries into transformational new energy technologies (i.e. identification of exciting new scientific phenomena and their application to disruptive new energy technologies)."

The letter listed the following program areas of interest:

- Electrification of transport
- Advanced renewable transportation fuels
- Advanced vehicle technologies
- Low cost, scalable, dispatchable centralized renewable power
- Future grid (advanced "smart grid" technologies)
- Distributed energy technologies
- Efficient end use of energy
- Low carbon fossil energy technologies
- Energy materials of the future
- Industrial efficiency.

Other countries are taking other initiatives, and priorities will differ, but the power and ambition of the DOE agency's approach, and the funding amount, certainly shows a high degree of commitment to retain the initiative and develop new technologies as fast as possible, given the inevitable time constraints that Brian Arthur outlines.

CHINA'S CLEANTECH INITIATIVE

Hoegh-Guldberg (2010c) touched upon the massive efforts that China is exerting to develop new "cleantech" technologies. The central document is the 280-page *China Cleantech Report 2009* (Crachilov et al. 2009), which assembles a comprehensive picture of the various aspects of the technologies that are being pursued. The document is commercial, backed by over 80 leading international corporations and other organizations. The United States Commercial Service (Department of Commerce) is featured as the official market research partner.

The initiative responds to the fact that China's economic development has come at great environmental cost in terms of greenhouse gas emissions, strained water resources, land degradation including desertification and enormous landfill contamination – all caused by a development exceeding anything that has previously taken place in human history in such a short time. It is a process that may see China emerge as the world's largest economy during the next 20-40 years.

To achieve this, China's economic development must become environmentally sustainable out of necessity. China's requirements for greentech solutions are tremendous, and government policies back cleantech market development. China has laid the foundation for cleantech market growth, with the first signs of a green transformation already appearing.

The technologies are discussed in considerable detail in the report, under the following headings supplemented by some of the possible technologies listed in the report:

- Cleaner conventional energy (cleaner coal through carbon capture and storage, cleaner oil, cleaner gas, nuclear energy)
- Renewable energy utilizing the country's extensive solar and wind resources (solar photovoltaic and concentrated solar power, wind power, bioenergy)
- Electric power infrastructure (overcoming shortages, grid connectivity for renewable sources, minimizing energy losses)
- Cleaner transportation (roads, cleaner automotive fuels, hybrid cars; increasing railroad densities; airports and air transport; waterway transport)
- Green building (overcoming negative environmental impacts; introducing green building technology still rare in China; huge potential seen)
- Cleaner industry (energy efficiency, air and water pollution, solid waste)
- Clean water (water extraction, treatment, distribution, and use; wastewater treatment).

It was suggested in Hoegh-Guldberg (2010c) that China's enormous need to become environmentally sustainable may help provide the commercial mechanism needed to secure international agreement on climate change, which stalled at the UNFCCC conference in Copenhagen in December 2009. A number of observers made the point that a successful conclusion of a long-term binding agreement depended on cooperation between the United States and China, with a direct emphasis on decarbonization to prevent the negotiations from bogging down on overall emissions targets. The list above is a living example of how to use a great variety of avenues towards decarbonization.

CLASSIFICATION CRITERIA IN TECHNOLOGY REVIEWS

Like other topics to be approached in a world threatened by accelerating climate change, the subject matter has mushroomed compared with 2005, when the Florida Keys project was first planned. New literature is added to the knowledge base daily. It is a challenge in these circumstances to achieve the right focus on a complex situation, in a project originally conceived for a simpler world.

As outlined in the next main section, a number of sources have been useful in providing the beginning of a framework, notably a review article on solutions to global warming, air pollution, and energy security (Jacobson 2009), and *Ten Technologies to Save the Planet* (Goodall 2008). They are supplemented by lists of preferred technologies in other sources, and descriptions of individual technologies. The main challenge was to put all the information into a manageable framework.

Two criteria help here. First, technologies that are potential "solutions to climate change" can be classified into three groups (Cosier 2008):

1. Energy technology (say, roughly 50% of the solution according to Cosier)

2. Energy efficiency (25%)
3. Landscape (or land) management (25%).

Cosier regards the third component as the heart of driving a 21st century economic revolution. He calls it "the economics of nature, because it is a giant step towards putting an economic value on the services that nature provides us. Reducing the destruction of these stores of carbon, by reducing land clearing, and by increasing carbon stocks through revegetation and improving soil carbon, makes landscape management a fundamental part of managing the CO_2 balance in the atmosphere. "

Such land management technologies have been labeled "green carbon" as distinct from "blue carbon" that covers the role of coastal areas – notably mangroves, salt marshes, and seagrass beds – in transferring CO_2 to the ocean on a semi-permanent basis (Nellemann et al. 2009).

Notwithstanding Cosier's statement, a major hurdle for these technologies is the difficulty of putting economic values on particular ecosystems *and* how they link up. National accounting for environmental values is falling seriously short of providing true and acceptable estimates (Hoegh-Guldberg 2010b). Despite some recent progress, this work still concentrates on local ecosystems and specific natural resources. It excludes the general impact of climate change, and how ecosystems connect. An attempt to value the Great Barrier Reef ecosystem (Oxford Economics 2009) is unconvincing at best as discussed in the main report, Section 6.5.

Finally, our focus is not only on technologies that reduce the threat of climate change but also on those that assist the least developed countries. Both are devices for "saving the world", but the second group act as "enabling technologies" aimed at reducing poverty as well as greenhouse gas emissions.

When poverty is recognized as the twin of climate change, which makes much sense in the context of scenario planning, "enabling technologies" show up strongly (including "purposed systems" as defined by Brian Arthur). They include microcredit, specially created for the developing world, and cell phones, which were not but have proven extraordinarily successful there. Enabling technologies and purposed systems assist alternative smaller-scale solar, biofuel and other technologies appropriate for developed economies in achieving success. The concluding main section of this paper discusses this further.

CLASSIFICATION OF TECHNOLOGIES: MAIN SOURCES

The two main sources, as already mentioned, are Jacobson (2009) and Goodall (2008). They are treated under separate headings, followed by other references including the "wedge" analysis by Pacala and Socolow (2004, also in Socolow et al. 2004), which demonstrates that there is no single technological solution to climate change – no "silver bullet".

SOLUTIONS TO GLOBAL WARMING, AIR POLLUTION AND ENERGY SECURITY

Mark Jacobson (2009) considers the following electric power sources: solar photovoltaics (PV), concentrated solar power (CSP), wind turbines, geothermal power plants, hydroelectric power plants, wave devices, tidal turbines, nuclear power plants, and coal power plants fitted with carbon capture and storage (CCS) technology. He also considers two liquid fuel options: corn-E85 and cellulosic-E85 (85% ethanol, 15% gasoline). He then examines their ability to address the problems mentioned by powering new-technology vehicles, including battery-electric vehicles, hydrogen fuel cell vehicles, and E85-powered flex-fuel vehicles. [6]

The criteria used in Jacobson's assessment are wide-ranging, the most important being CO_2-equivalent emissions and human mortality from air pollution, followed by land use and water demand. Other criteria included effects on wildlife, thermal, chemical and radioactive pollution, disruption to energy supply, and operational reliability.[7]

From an analysis in which he develops a score based on his assessment criteria, Jacobson finds that combinations of energy source and vehicle type fall into four tiers:

1. The most efficient combination is battery-electric vehicles (BEV) based on wind power. The overall number two is hydrogen fuel cell vehicles (HFCV), despite the vehicle type being less efficient than BEVs and not otherwise demonstrated as a top option.
2. All combinations in Tier 2 are with BEVs. The top power source is concentrated solar power (CSP) followed by geothermal, photovoltaic, tidal, and wave in that order. Note that all the top options are renewables: wind, water, solar (WWS).
3. Tier 3 is in the "less desirable" range, again comprising power sources for BEVs: hydro, nuclear, and coal-CCS. They have nearly equal overall scores according to the criteria set up, but hydroelectric power squeezes into the "recommended" range as being clean on climate and health, and being "an excellent load balancer". The other two power sources are not recommended.
4. Neither are the ethanol options. They rated lowest overall and in respect to climate, air pollution, land use, wildlife damage, and chemical waste. Cellulosic-E85 ranked lower than corn-E85 overall, primarily due to its potentially larger land footprint based on new data and its higher upstream air pollution emissions compared with corn-E85.

In short, the criteria cover the costs of *externalities* not only of greenhouse gases but also other sources of pollution, damages to the environment, and damages to human health. But renewable costs are rapidly becoming competitive with coal, with wind expected to be the least costly of all sources (Jacobson and Delucchi 2009). Solar energy, still fairly costly, is expected to be competitive by 2020 (Fthenakis et al. 2009). Generally, the field is likely to change considerably, as already seen in relation to new fermentation technology.

In the interim, however, renewable power will be generally more costly than fossil power. Some combination of subsidies and carbon taxes are therefore required – justified by the

[6] These options are among the most commonly discussed. Other fuel options include algae, butanol, biodiesel, sugar-cane ethanol and hydrogen combustion, electricity options such as biomass, vehicle options such as hybrid vehicles, heating options such as solar hot water heaters, and geoengineering (Jacobson 2009). Some of these options are currently gaining prominence, notably fermentation technologies such as biodiesel.

[7] He also examined the loss of opportunity costs incurred by going down a particular technological path rather than another – finding that the promotion of ethanol, nuclear or carbon capture and storage is backing the wrong technologies at a cost of lost opportunity. This conclusion is controversial and subject to challenge, depending on the geographical setting. Ethanol production in Brazil, for instance, has proven highly successful over 30-40 years despite the alternative use of sugar cane as a food source. More recently, new developments in fermentation technology are enabling the cane and other biomass to be more efficiently and fully utilized, and to combine production of ethanol and sugar (Villadsen 2007, Attfield 2009).

hitherto largely uncovered cost of externalities. Jacobson and Delucchi (2009) suggest that a feed-in-tariff (FIT) program to cover the difference between generation cost and wholesale electricity prices is especially effective in scaling up new technologies. “Combining FITs with a so-called declining clock auction, in which the right to sell power to the grid goes to the lowest bidders, provides continuing incentive for WWS developers to lower costs. As that happens, FITs can be phased out.” (p 45)

As of 2009, feed-in tariff policies have been enacted in 63 jurisdictions around the world, including Australia, Austria, Belgium, Brazil, Canada, China, Cyprus, the Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Iran, Ireland, Israel, Italy, Korea, Lithuania, Luxembourg, the Netherlands, Portugal, Singapore, South Africa, Spain, Sweden, Switzerland, and a dozen states in the United States. It was gaining momentum in China, India and Mongolia. The policies applied mainly to domestic photovoltaic solar systems.[8]

Jacobson and Delucchi (2009) present a plan for the world to switch to renewable technologies by 2030, and give the following estimates of needed capacity (assuming financial and technical success of individual technological developments):

- *Water*: 1.1 terawatts (9% of supply), mainly geothermal plants and hydroelectric plants, plus small tidal turbines.
- *Wind*: 5.8 TW (51% of supply). predominantly wind turbines with a small contribution from wave converters.
- *Solar*: 4.6 TW (40% of supply). 1.7 billion rooftop photovoltaic systems, plus about 90,000 concentrated solar power plants and photovoltaic plants @ 300 MW.[9]

These estimates were based on Jacobson (2009), whose later sections deal with available resources for each technology, their effect on climate-relevant emissions (CO_2e), land and ocean use, and other variables included in the analysis.

The plan includes only technologies that work or are considered close to working today on a large scale, rather than those that may exist 20 or 30 years from now. The same applies to the technologies analyzed in Jacobson’s (2009) review, which formed the base. This is significant in view of Arthur’s (2009) finding that the introduction of new technologies may take decades. The notes following below include information, wherever possible, on the first appearance of particular technologies in a form relevant in a modern context .

[8] Wikipedia, “Feed-in tariff”. Accessed March 8, 2010.

[9] Actual clean energy schemes are becoming influential, as shown by the following representative examples. Launched in 2008 by Al Gore, *Repower America* (http://www.repoweramerica.org/us/about/) was introduced as a bold plan to "repower" the United States with 100% clean electricity and revitalize the national energy infrastructure. In July 2009, Gore launched *Safe Climate Australia*, which has similar objectives. Its purpose is “to identify and catalyze action on the societal transformations and solutions needed to achieve a safe climate for Australia, and for the planet, at emergency speed. The structural change achieved in the next ten years is crucial.” http://www.safeclimateaustralia.org/.

“TEN TECHNOLOGIES TO SAVE THE PLANET”

While Mark Jacobson’s technology analysis concentrates on energy technologies rather than efficiency or land management, Goodall‘s ten technologies (2008) come from all three categories:

- Energy technologies include wind, solar, the oceans, motor fuels from cellulose, and carbon capture. A sixth technology concentrates on the need to produce the greenest possible cars, where he sees the solution to be battery-only electric cars. Hydrogen as a fuel is an undeveloped technology with no infrastructure where an enormous investment would be needed. Meanwhile, smaller more efficient conventional engines and hybrids still emit CO_2 while filling a void. Goodall considered low-carbon fuels from agricultural products (biofuels) as less desirable because they come from sugar cane, wheat or corn. As noted previously, developments in fermentation technology may be changing this perception as the utilization of the biomass improves.
- A seventh technology is a hybrid combining fuel cells (an energy technology) and district heating (an energy efficiency measure that is actually quite old technology). The eighth, “super-efficient homes,” is all about energy efficiency.
- The two final technologies are in the realm of the third class that Cosier (2008) called landscape management: sequestering carbon as biochar, and soils and forests (improving the planet’s carbon sinks).

Goodall asks (p 254): “If we make substantial progress in each of the ten opportunities described in this book, will we be able to reduce fossil fuel use in advanced economies fast enough? And can we counterbalance the emissions of methane and other greenhouse gases by improving carbon storage in soils and plant matter?” The short answer is yes, but it is a big challenge.

He notes first that the energy footprint of the average person in Britain (“a fairly typical advanced economy”) is about 50,000 KWh per person per year, or a continuous energy use of 5,100 watts per person. The bulk of this comes from burning of fossil fuels (some from nuclear energy and a still tiny amount from renewables).

Electricity accounts for about 1,900 watts per person, but this is expected to increase to 2,750 watts due to electric cars (300 watts), replacing gas and oil in manufacturing (300 watts), and increased distance heating (250 watts). Goodall expects this to be replaceable by 2025 with wind power (25%), solar power, mostly concentrated solar power (CSP) in Africa (25%), tidal and wave technology (15%), fuel cells and biomass combined heat and power (10%), and carbon capture and/or nuclear (25%).

“Clearly this is a substantial challenge, but it is far from impossible.” (p 257) Offshore wind turbines would fill an area of 100 by 160 km, a small percentage of Britain’s continental shelf, and 25% of electricity demand is already met by wind in some European countries. The primary obstacle for solar power generated in deserts is the need for a sustained program of construction of long-distance DC transmission lines, while the growth of electricity supply from tides and waves depends on “continued entrepreneurial activity among the plethora of small firms constructing innovative devices.” (p 258) The target for fuel cells also depends on technical progress, particularly towards reducing the cost of cells designed to produce electricity for large commercial buildings. Using biomass for combined heat and power depends on the ready availability of woody materials for fuel, rather than technological advances. (p 258)

This leaves 25% of the total need for power to be met either through coal-CCS (if still using fossil fuels), nuclear technology, or both. CCS technology is a long way from commercial availability. "Indeed, it may be 2020 before we understand how to capture CO_2 with reasonable efficiency. But then it should be possible to add carbon capture equipment to most existing coal-fired power stations." (p 258)

Measures to reduce gas demand (currently 1,400 watts per person) would come from space insulation (300 watts), fuel cells (300 watts), replacement by electricity in manufacturing (250 watts), conversion to electric heating (200 watts), and biomass heating (100 watts) – leaving remaining gas demand at 250 watts. Oil demand (currently 1,650 watts per person) would be reduced by electric cars and vans (600 watts), cellulosic and other renewable fuels (200 watts), fuel cells and biomass heating (100 watts), and replacement by electricity in manufacturing (100 watts) – leaving remaining oil demand at 650 watts.

Finally, coal used for other than electricity generation in Britain is about 150 watts per person, mainly for heavy industrial purposes such as in blast furnaces to make iron where it is unlikely to be replaced. The use in other countries varies substantially from this estimate.

Based on Britain, the total need for energy from carbon sources could therefore fall to about one-fifth in a typical advanced economy. "This figure conveniently matches most scientific assessments of the emissions reductions required in rich societies."[10] (p 262) However, there are other greenhouse gases, especially methane and nitrous oxide, and Goodall reckons that all CO_2 emissions from fossil fuels should be eliminated to be on the safe side. He relies on soil improvement and biochar for this, as "we can reasonably aim to increase the carbon stored in soils by at least 1 per cent of the weight of the soils themselves." (p 262) The offset of the 1,050 remaining watts per person would be an area as small as 10 by 10 m per annum until the economy is completely decarbonized.

One major problem remains (p 263): "Sequestering carbon in the soil requires us to add plant matter, whether in the form of biochar, longer roots or greater amounts of humus. We also need to use wood and straw for making cellulosic ethanol for fuel cells and car engines and for providing the fuel for biomass heating plants. If guesses in this chapter are approximately correct, we may need 800 continuous watts of our total per capita energy need to come from plants and trees. This is about the same amount of energy we might get from wind or solar power in 2025."

The demand on land to achieve this is very large – say 15% of the area of France if that country chose to use its own land to grow the woody matter it needed. It might make more sense, says Goodall, to grow the wood or straw in developing countries, which would also have the benefit of increasing incomes there, and provide an incentive to reforest large

[10] It is not clear from this whether allowance has been made for population growth. All the estimates, of course, are informed guesses. The stated ambition is to reduce energy demand by 80% by 2025 (whether per capita or totally). Targeted 80% reductions in emissions are usually by 2050.

areas. "But it will still require a significant percentage of the world's usable land area to be given over to renewable forests for making the raw material for cellulosic ethanol." (p 264)

Goodall explains the following omissions from the "list of 10":

- Nuclear power, apart from its safety and storage problems and its long construction lead times, has the worst record of increasing costs of any major technology. In contrast to the cost reductions that can realistically be expected from the major renewable energy technologies, costs per KWh expressed in constant prices have increased strongly over thirty years. (p 268)
- Only one energy efficiency technology gets into the list – better insulated homes. The explanation is simply that house insulation is the single most energy efficiency improvement the world can make, both in cold and warm countries. Any other domestic efficiency measures are dwarfed in comparison. This is not to say, of course, that the appliance and other industries should not continue to improve energy efficiencies. But more could be gained by improving the internal combustion engine and reversing the wasteful use of electricity in offices. Office workers use much more electricity in a 40-hour working week than at home, due to wasteful use of computers, poor building design, and general electricity use. (p 272)
- The last technology missing the list of ten is geoengineering. It is regarded at most as a fallback position – in case reductions in emissions fail to develop or temperature increases begin to induce dangerous instability to the climate. (p 272) It is a contingency planning device which recognizes the environmental risks involved. Goodall mentions three possible geoengineering options (pp 272-276) which are best taken up in the section on individual technologies.

STABILIZATION WEDGES

In 2004, two Princeton scientists introduced the concept of "stabilization wedges" as a proposed means of solving the climate problem with current technologies (Pacala and Socolow 2004, Socolow et al. 2004). This probably did more than anything to bring home the message that while humanity already possesses the scientific, technical and industrial know-how, there is no single solution (no "silver bullet") to fix it all. While the best "wedges" may have changed in a

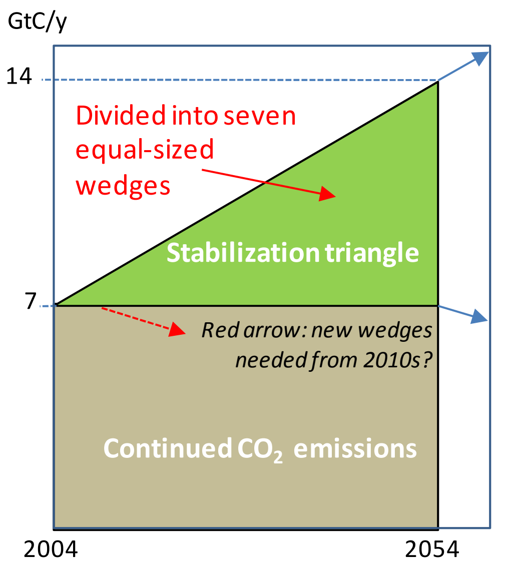

Figure 1 shows the basic Socolow/Pacala model. The stabilization triangle limits CO_2 emissions to present levels. Each of seven technology "wedges" increases linearly until in 50 years it accounts for 1 GtC annually of reduced emissions. The seven-wedge assumption is based on a stabilization level of 500 ppm CO_2 and emissions growing by 1.5%/year.

The red arrow is a new addition, showing the path of new "below-the-line" wedges as the climate change issue gains urgency.

rapidly changing technological environment, the wedge concept itself continues to make sense.

Socolow and Pacala adopted a half-century perspective to demonstrate how to deal with climate change relative to a "business-as-usual" scenario, in which they assumed that carbon emissions would continue to increase by 1.5% annually, which was the average for the previous 30 years. This would double annual emissions in 50 years.

The proposed solution was to accept the level of current CO_2 emissions (7 gigatons of carbon annually) and to cut future growth by introducing seven technologies as "wedges" which would each be capable eventually of reducing carbon emissions by one gigaton per year. The frame of reference appears to be a stabilization target of 500 ppm, which according to climate models at the time would be compatible with a global average temperature increase of around 3^{O}C.

The authors said themselves that if emissions were to increase by 2% per annum, about 10 "wedges" would be needed, and if the annual increase was 3%, the number of "wedges" would increase to about 18. Today, five years or more after the research, the assumptions need to be updated, as all evidence has needed updating since the middle of the decade. One paper has updated the basic diagram above, setting the level of continuous annual emissions not at 7 GtC from 2004-2054, but at 11 GtC from 2020-2070, saying this would mean that CO_2 levels would reach 1,000 ppm by the end of the century with a best estimate global warming average of $+5.5^{O}$C (Romm 2008). The author justifies this as follows:

"Carbon emissions from the global consumption of fossil fuels are currently above 8 GtC per year and rising faster than the most pessimistic economic model considered by the IPCC. Yet even if the high price of energy from fossil fuels and power plants combines with regional climate initiatives to slow the current rate of growth somewhat, we will probably hit 11 gigatons of carbon emissions per year by 2020." (Romm 2008, p 85)

To be compatible with the perceived need to remain below a $+2^{O}$C target, which is seen increasingly as necessitating a CO_2 target of 350 ppm or less, the comparison with "business-as-usual" would mean that emissions could not be allowed to remain at current levels for 50 years. IPCC's Fourth Assessment Report and numerous more recent analyses show that emissions, currently growing at over 2% per annum, need to peak and then decline from the mid-2010s to secure these targets. This means finding additional "wedges" to extend the stabilization triangle into what is shown as "continued fossil fuel emissions." So the downward-pointing arrow beyond 2054 should now start four decades previously. The red arrow on Figure 1 pointing downwards from about 2014 suggests this is a new and very serious challenge indeed, superimposed on the already defined stabilization triangle.

This calls for a dramatic increase in every nation's sense of urgency, but it doesn't invalidate the wedge concept. A multiple-technology solution to the problem is still needed, the difference being that more wedges will be needed. Pacala and Socolow suggested 15 wedges, nine of which were energy technologies, four aimed at improved energy efficiency, and two at land management. Each option would indicate the effort needed in 2054 for the wedge in question. Their options and associated key issues are listed and numbered as in the original paper; some statements of course are debatable and possibly outdated six years after the original paper was published.

Energy efficiency

1. Efficient vehicles: Increase fuel economy for 2 billion cars from 30 to 60 mpg. Issues: Car size, power.
2. Reduced use of vehicles: Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5000 miles per year. Issues: Urban design, mass transit, telecommuting.
3. Efficient buildings: Cut carbon emissions by one-fourth in buildings and appliances projected for 2054. Issue: Weak incentives.
4. Efficient baseload coal plants: Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today). Issue: Advanced high-temperature materials.

Energy technologies

5. Gas baseload power for coal baseload power: Replace 1,400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power). Issue: Competing demands for natural gas.
6. Capture CO_2 at baseload power plant: Introduce CCS at 800 GW coal or 1,600 GW natural gas (compared with 1,060 GW coal in 1999). Comment: Technology already in use for H_2 production.
7. Capture CO_2 at H_2 plant: Introduce CCS at plants producing 250 Mt H_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources). Issues: H_2 safety, infrastructure.[11]
8. Capture CO_2 at coal-to-synthetic fuels plant: Introduce CCS at synfuel plants producing 30 million barrels a day from coal if half of feedstock carbon is available for capture (200 times the South African company Sasol, which produces most of that country's diesel fuel). Issue: Increased CO_2 emissions, if synfuels are produced without CCS.[12]

   Geological storage (items 6 to 8): Create 3,500 Sleipners.[13] Issues: Durable storage, magnitude and cost of program.

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[11] Pacala and Sokolow (2004) was part of a special section of *Science*: 'Toward a hydrogen economy', which may explain the inclusion of this suggested wedge. Turner (2004) in a subsequent paper in the same issue wrote (p 972): "Hydrogen can be generated from water, biomass, natural gas, or (after gasification) coal. Today, hydrogen is mainly produced from natural gas via steam methane reforming, and although this process can sustain an initial foray into the hydrogen economy, it represents only a modest reduction in vehicle emissions as compared to emissions from current hybrid vehicles, and ultimately only exchanges oil imports for natural gas imports. It is clearly not sustainable."

[12] Synthetic fuels are produced from the Fischer-Tropsch process, developed in coal-rich but oil-poor Germany, to secure sufficient transport fuel during World War Two. Feedstocks are coal (via a gasification process) or natural gas. In 2009, chemists working for the U.S. Navy investigated the use of the process for generating fuels using hydrogen by electrolysis of seawater. This may lead in time to a kerosene-based jet fuel.

[13] Norwegian gas field Sleipner, 250 km west of Stavanger in the North Sea, is the oldest plant that stores CO_2 on an industrial scale. Creating 3,500 similar plants seems ambitious, requiring a huge sustained program.

9. Nuclear power for coal power: Add 700 GW (twice the current capacity). Issues noted by Pacala and Sokolow: Nuclear proliferation, terrorism, nuclear waste disposal.

10. Wind power for coal power: Add 2 million 1-MW-peak windmills (50 times the current capacity) “occupying” 300,000 km^2, on land or offshore. Comment: Multiple uses of land because windmills are widely spaced.[14]

11. PV power for coal power : Add 2,000 GW-peak PV (700 times the current capacity) on 2 x 10^6 ha. Issue: PV production cost

12. Wind H_2 in fuel-cell car for gasoline in hybrid car: Add 4 million 1-MW-peak windmills (100 times the current capacity). Issues: H_2 safety, infrastructure.

13. Biomass fuel for fossil fuel: Add 100 times the current Brazil or U.S. ethanol production, with the use of 2.5 million km^2 (one-sixth of world cropland). Issues: Biodiversity, competing land use.

Land management (forests and agricultural soils)

14. Reduced deforestation, plus reforestation, afforestation, and new plantations: Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 million ha of new tree plantations (twice the current rate). Issues and comments: Land demands of agriculture, benefits to biodiversity from reduced deforestation.

15. Conservation tillage: Apply to all cropland (10 times the current usage). Issues: Reversibility, verification.

Comments on original list of wedges

In his critique of the original paper, four years after its publication, Romm (2008) suggested the following wedges to keep CO_2 emissions flat between 2020 and 2070 (eleven, totaling the replacement of 11 gigatons of carbon):

- Efficient buildings: savings totaling 5 million GWh
- Efficient industry: savings totaling 5 million GWh, including co-generation and heat recovery
- Vehicle efficiency: all cars 60 miles per US gallon (>25 km/liter)
- Coal: 800 GW-sized plants with all the carbon captured and permanently sequestered
- Nuclear: 700 new GW-sized plants (plus replacement plants)
- Concentrated solar thermal electric: 1,600 GW peak power
- Solar photovoltaics: 3,000 GW peak power
- Wind power: 1 million large wind turbines (2 MW peak power)
- Wind for vehicles: 2,000 GW wind, with most cars plug-in hybrid electric vehicles or pure electric vehicles

[14] The required area is approximately the same as Arizona, the sixth-largest state (295,000 km^2)

- Cellulosic biofuels: using up to one-sixth of the world's cropland
- Forestry: end all tropical deforestation.

Lynas (2008) discusses the Pacala and Socolow concept in some detail towards the end of *Six Degrees.* He reminds us that we need seven wedges just to stabilize global emissions at their current levels, and also highlights the sheer scale needed to make an impact, in particular for renewables relative to current levels of production (p 295). His final reminder is that we need to limit the global average temperature increase to 2^{O}C, which will necessitate more wedges (in line with the "red-arrow addition" on Figure 1).

The most controversial technology options according to Lynas (2008) are:

- Nuclear power, despite being a low carbon source with a proven track record in electricity generation. While the technology appears to be increasingly risk-free, it keeps raising the dangers of nuclear weapons proliferation and accidents, and the waste problem is unresolved. It may remain a wedge despite Lynas's assessment, as nuclear technology seems to be moving fast – further discussed later.
- Biofuels, especially from crops. Much of the biodiesel used in Europe comes from palm oil plantations in Indonesia and Malaysia, which have replaced large areas of rainforest. (pp296-297) The ethanol wedge would (also) require one-sixth of the world's cropland. The technology for cellulosic ethanol is still being developed (though recent evidence looks promising); other problems include that the raw materials would otherwise be plowed back into the land, and plantations to secure the materials may expand into currently marginal areas, further reducing biodiversity in the remaining wild spaces of the planet (p 299)

Lynas suggests seven wedges which would keep emissions constant at 7 GtC:

- Energy efficiency: Halve driving distances per vehicle; double vehicle fuel efficiency; increase energy efficiency in buildings; and in fossil-fueled power stations
- Energy technology: Wind turbines; solar panels (PV on roofs preferred); make difficult choice between coal-CCS and replacing coal with gas power stations
- Land management: Stop deforestation and promote reforestation (his top preference).

To reduce emissions to ensure a +2^{O}C target, Lynas suggests the following additional wedges:

- Energy efficiency: Live less consumptive lifestyles; adopt more localized patterns of behavior
- Double quantity of wind turbines.

Naturally, many other options will be put forward, and the list will change as some technologies achieve greater technical and economic breakthroughs than others, and with the shifting balance between energy technology, energy efficiency, and land management options.

The current tendency seems to be to recommend technological solutions first, and look at energy efficiency options last. Lifestyle is, however, a prominent feature of the four scenarios, embedded in the original IPCC storylines. The extent to which populations can be persuaded to modify their lifestyles, or in the case of the main emerging countries such as China, India, other Asian countries, Brazil and other Latin American countries, and the emerging eastern European economies, to refrain from copying the current lifestyles of rich countries, has to be carefully considered. Current indications are that western lifestyles will be copied.

REVIEW OF TECHNOLOGIES

This review comes from a variety of sources and does not claim to be exhaustive, just to. give a reasonably meaningful description in a limited space. The starting point is Jacobson (2009), followed by Goodall's *Ten Technologies to Save the Planet* (2008) and other sources, including those describing the history of particular technologies. They show that many years can elapse between the discovery of a natural *phenomenon* and the *invention* leading to the development and commercial integration of a technology (Arthur 2009). The technologies are divided into the Cosier (2009) headings of energy technologies, geoengineering options (headlined separately because they represent a different magnitude of potential energy technologies), energy efficiency measures, and landscape (land) management, including coastal management as a separate category.

ENERGY TECHNOLOGIES

Solar photovoltaics (PVs)

The photovoltaic effect is the operating principle of the solar cell, in which the capture of light (photons) results in the creation of an electric current as electrons are transferred from one material to another resulting in the build-up of a voltage between two electrodes. It was discovered in July 1839 by then 19-year old Alexandre-Edmond Becquerel, who reported his findings to the French Academy of Sciences later in that year.[15]

Charles Fritts, an American, described the first solar cells made from selenium wafers in 1883. It was 1954 before Bell Laboratories made the first PV device providing useful amounts of electricity, and early 2000s before PVs experienced rapid commercial growth, rapid cost reduction, and large technological breakthroughs.[16] The payback period has halved and thin-film panels have even better energy balance because they require much less energy to produce (Goodall 2008, p 59). The technology is versatile because panels can be mounted in small numbers on roofs or combined into farms ranging from 10-60 MW capacity. The largest problem – shared with other technologies according to Goodall – is scaling up the manufacturing rate to make a sizeable dint in global greenhouse emissions in time (p 58). But he notes that the scope for unexpected and truly revolutionary advances in PV technology is at least as great as for any other technology he examined.

[15] Wikipedia, 'A. E. Becquerel', as at February 27, 2010.

[16] http://www.sunlightelectric.com/pvhistory.php.

Concentrated solar power (CSP)

In the 1860s, French mathematician August Mouchet proposed an idea for solar-powered steam engines. In the following two decades, he and Abel Pifre constructed the first solar powered engines and used them in a variety of applications. These engines became the predecessors of modern parabolic dish collectors. In 1969, the Odeillo solar furnace in southern France was constructed, featuring an eight-storey parabolic mirror. However, it was not until the 1980s that the first large-scale solar thermal electric generators were built.[17]

Concentrated Solar Power is now undergoing a renaissance in the solar-rich areas of the world including Spain and the United States Southwest, according to Emerging Energy Research (EER), which analyzes clean and renewable energy markets on a commercial basis. EER notes that solar CSP is the fastest growing utility-scale renewable energy alternative after wind power, with up to $20 billion expected to be invested in the technology over the next five years.[18] In the US Southwest, utilities are showing increasing interest in the deployment of CSP plants to meet the requirements of state renewable portfolio standards (DOE 2009).[19]

As at early 2010, there is 679 MW of installed CSP capacity worldwide and more than 2000 MW under construction. The US is the market leader in terms of installed capacity with 63% market share, followed by Spain with 32% of operating capacity. Spain accounts for the largest share of projects under construction with almost 89%, and may topple the US as global leader in installed CSP capacity by 2013 (Torres et al. 2010).

Other areas attracting attention as potential CSP sites include the Middle East and North Africa ("MENA"), as well as India, Australia and China. The two latter countries are reported to be investigating the combination of CSP and biomass technology, using the high heat generated by the CSP plant to break down biomass such as algae into hydrocarbon fuel and chemicals. This would help bypass first-generation biofuels such as food plants, going straight to more acceptable sources.

The Australian National University in Canberra has worked for many years on parabolic dish solar concentrators and demonstrated a 400m^2 parabolic dish solar system in 1994.

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[17] http://www.rise.org.au/info/Tech/hightemp/index.html. CSP, as discussed in the current section, covers large high-temperature systems. Solar thermal systems also include generally much smaller low- and medium-temperature systems for swimming pool, domestic hot water and space heating, and in passive solar building design.

[18] From http://www.emerging-energy.com/, as at October 2009. The website keeps changing and much material is exclusively available for the company's clients, including comprehensive recent reports on the USA and Europe. Other information sources provide an ongoing review of new developments, including *CSP Today* which offers free newsletters and a free summary of a high-priced global analysis (Torres et al. 2010). The summary provides an adequate picture for our purposes.

[19] Florida Power & Light (FPL) began construction in its home state at the Martin Next Generation Solar Energy Center in Indiantown, western Martin County, in December 2008, with completion expected at the end of 2010. It is the first hybrid solar facility in the world to connect to an existing combined-cycle power plant and at 75 MW will be the largest solar thermal plant outside of California. The annual generation is expected to be about 155,000 MWh or enough power for 11,000 homes (http://www.fpl.com/environment/solar/martin.shtml).

Commercializing the “Big Dish” technology involved a re-design of the concept for mass production, undertaken after a partnership was brokered in 2005 between the university’s Solar Thermal Group and the solar technology firm Wizard Power, also located in Canberra. Construction of a first prototype on the ANU campus began in the first quarter of 2008, and initial tests were carried out in June 2009 (Lovegrove et al. 2009).

Wizard Power’s attempts to commercialize several solar-biofuel processes are also based on ANU research work. The Big Dish technology can create maximum temperatures of over 2000°C, with a typical operating range of 400-1400°C. However, the jury remains out whether to develop solar-biofuel technology in conjunction or commercialize at least one of the two technologies first (Wagg 2010).

A German consortium is studying the feasibility of building a collection of CSP plants in North Africa and Saudi Arabia, which could meet 15% of Europe’s electricity needs by 2050. The project, called Desertec, plans to transmit the electricity via 20 high-voltage DC power lines across to Europe, where it would join a supergrid conveying power from North Sea wind turbines, [20] Scandinavian hydroelectric dams, Icelandic hot rocks, and eastern European biofuels. The major problems are water supply for heat exchange (air cooling is less efficient and more expensive), and supply security.

A Nigerian entrepreneur has set up an organization to promote the use of African sunshine for Africans (Pearce 2009).

While PV cells convert photons directly from sunlight into electricity, CSP technology generates power from the sun by concentrating the rays on to a liquid. “The best established solar thermal technology … uses long parabolic troughs covered with reflective material to concentrate the sun’s powers on to a thin tube, called a receiver, in the center of the parabola. A good solar collector can focus about a hundred times the power of the sun on to this receiver. The tube contains water or, more usually, oil, which is heated to over 400^{O}C in full sun. The hot oil is passed through water, with which it exchanges heat. The water rapidly heats up, boils, and then turns into electric steam, ready for powering a rotating turbine, in exactly the same way as it would in a coal-fired power station.” (Goodall 2008, p 60)

There are four primary CSP plant designs (described in DOE 2009, Pearce 2009, and elsewhere). The description below is mainly from Wikipedia, as at March 2010:

- **Parabolic solar trough designs** described in the previous paragraph. The main existing plants in California, Nevada, and Spain are of this type.
- **Power towers** use an array of flat, moveable mirrors, called heliostats, to focus the sun's rays upon a collector tower (the receiver). The prototype plant is in Spain but several new projects are being planned or constructed in Southern California including the

[20] The wind and hydropower components have moved closer to reality with the formation, on March 8, 2010, of “Friends of the Supergrid” (FOSG), initiating a $46 billion project to progress policy towards the construction of a pan-European offshore supergrid. The initial participants are 10 major global corporations based in Europe (FOSG 2010). The project links up with a recent decision by nine northern and western EU member states (the UK, Ireland, Norway, Denmark, Germany, the Netherlands, Belgium, Luxembourg, and France) to sign a political declaration for the "North Seas Countries Offshore Grid Initiative". The German company Siemens is a prominent member of both the FOSG and Desertec projects.

largest solar power commitment ever made by a utility (the Pacific Gas and Electric Company), and in Israel, Spain, and South Africa.

- **Linear Fresnel** reflector power plants use a series of long, narrow, shallow-curvature (or even flat) mirrors to focus light onto one or more linear receivers positioned above the mirrors. These systems aim to offer lower overall costs through simpler design. The Fresnel solar power plant PE 1 of the German company Novatec Biosol went into commercial operation in southern Spain in March 2009 with an electrical capacity of 1.4 MW; a recent prototype in Australia has led to a proposed 177MW plant near San Luis Obispo in California; a Belgian prototype has generated several other prototype projects.
- **Dish/engine systems** produce electricity directly from heat using a large parabolic disc, usually in combination with a Stirling engine (an external combustion engine that isolates its working fluid from the energy input supplied by an external heat source). Disc systems can generate high temperatures from high concentrations of light. Two Californian power companies have announced agreements to purchase solar-powered Stirling engines to generate power plants between 300 and 900 MW, but it is unclear whether the technology has progressed beyond the construction of a small test plant.

All designs use a small amount of water for mirror cleaning, and all except dish/engine systems operate a steam cycle which require water for steam makeup and then a substantial amount of water for heat rejection, similar to water-cooled fossil and nuclear plants.

Water cooling is preferred to minimize cost and maximize cycle efficiency, but there are concerns about mounting water shortages and air pollution. "Analyses indicate that the use of either direct or indirect dry cooling can eliminate over 90% of the water consumed in a water-cooled concentrating solar power plant. However, a combination of a reduction in power output and the added cost of the air cooling equipment is estimated to add roughly 2 to 10% to the cost of generating electricity, depending on the plant location and other assumptions. The use of hybrid parallel wet/dry cooling is estimated to reduce the energy cost penalty to below that of air cooling alone, while still saving about 80% of the water compared to a water-cooled plant." (DOE 2009, p 19). The technology continues to develop.

Wind energy

Wind technology has evolved through the entire recorded history of humankind, from the Fertile Triangle and India in the second millennium BC. Much later, small windmills for mechanical loads such as pumps and mills showed rapid growth in the 19th century.

The modern incarnation is the wind turbine, first built for electricity generation in 1986 and 1987 in Cleveland, Ohio, and Scotland. In the 1890s a Danish scientist, Poul la Cour, constructed wind turbines to generate electricity, which was then used to produce hydrogen. Wind farms were given a boost when long-distance electric power transmission became available and the wind generators no longer had to be built next to where the power was needed. Through the 20th century the technology developed in many countries, with Denmark in a leading position, including the development of offshore wind farms, and the first nation to derive a significant fraction of its electricity from that source.

Installed wind power capacity increased rapidly and steadily from 59 GW in 2005 to 158 GW in 2009 (+168%). The European Union accounted for 41 GW in 2005 and 75 GW in 2009, and the United States for 9 GW and 35 GW, respectively, according to the World Wind Energy Association. Wind power in 2008 accounted for 19% of stationary electricity production in Denmark, 13% in Spain and Portugal, and 7% in Germany and Ireland. Eighty countries around the world used wind power on a commercial basis in May 2009.

The main drawback of wind power is its intermittency, though this is less likely to cause problems when wind covers a relatively low proportion of total demand. New projects are often restricted locally or even on a national basis, due to their visual impact and effect on the environment. [21]

The efficiency of wind power generation increases with the turbine height since wind speeds generally increase with increasing height. So larger turbines capture faster winds and are generally sited in flat open areas of land, within mountain passes, on ridges, or offshore. Although less efficient, small turbines (1–10 KW, compared with 1 to 2 MW for typical wind farm turbines) are convenient for use in homes or city street canyons (Jacobson 2009).

Conservatively estimated, 13% of all stations worldwide have an annual mean wind speed above 6.9 m/s at 80 m (ranked as "Class 3" or greater), and are therefore suitable for wind power generation. Europe and North America have the greatest number of stations in class ≥3 (307 and 453, respectively), whereas Oceania and Antarctica have the greatest percentage (21 and 60%, respectively). Areas with strong wind power potential are in northern Europe along the North Sea, the southern tip of the South American continent, Tasmania, the Great Lakes region, and the northeastern and western coasts of Canada and the United States. Offshore stations experience mean wind speeds at 80 m that are about 90% greater than over land (Archer and Jacobson 2005).

Geothermal energy

Geothermal energy is extracted from hot water and steam below the Earth's surface. Hot springs were used through antiquity. Geysers and other underground sources have been used historically to heat buildings, industrial processes, and domestic water.

Modern geothermal technology was made possible by Lord Kelvin's invention of the heat pump as far back as 1852, and the idea of using it to draw heat from the ground was patented in Switzerland in 1912. But it was not until 1940s that the idea was successfully implemented. The first commercial geothermal heat pump for a commercial building was designed in 1946, and the first residential heat pump two years later. The technology became popular in Sweden after the 1973 oil crisis, and has been growing slowly in worldwide acceptance since then. The development of polybutylene pipe in 1979 greatly augmented its economic viability. By 2004 over a million geothermal heat pumps were installed worldwide providing 12 GW of thermal capacity. Each year, about 80,000 units are installed in the USA and 27,000 in Sweden.

[21] Main source: Wikipedia on wind power, accessed most recently on March 11, 2010.

Even in regions without large high-temperature geothermal resources (as exist in Iceland and the Cooper Basin in Central Australia),[22] a geothermal heat pump can still provide space heating and air conditioning. Like a refrigerator or air conditioner, the heat pump forces the transfer of heat from the ground to the application. In 2004, an estimated million geothermal heat pumps with a total capacity of 15 GW extracted 88 petajoules of geothermal energy for space heating. Global geothermal heat pump capacity is growing by 10% annually. [23]

Dry steam, flash steam, and binary are three major types of geothermal plants. Dry and flash steam plants operate where geothermal reservoir temperatures are 180–370^{0}C or higher. In the dry steam plant, about 70% of the steam re-condenses after it passes through a condenser, and the rest is released to the air. Since carbon dioxide, nitric oxide (NO), sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) in the reservoir steam do not re-condense along with water vapor, these gases are emitted to the air. In a flash steam plant, the liquid water plus steam from the reservoir enters a flash tank held at low pressure, causing some of the water to vaporize (''flash''). The vapor then drives a turbine. About 70% of this vapor is re-condensed. The remainder escapes with CO_2 and other gases.

A binary system is used when the reservoir temperature is 120–180^{0}C. Water rising up a borehole is kept in an enclosed pipe and heats a low-boiling-point organic fluid, such as isobutene or isopentane, through a heat exchanger. The evaporated organic turns a turbine that powers a generator, producing electricity. Because the water from the reservoir stays in an enclosed pipe when it passes through the power plant and is re-injected to the reservoir, binary systems produce virtually no emissions of CO_2, NO, SO_2, or H_2S. About 15% of geothermal plants today are binary plants (Jacobson 2009).

Hydroelectricity

Hydroelectric power is old and tested technology. It is currently the world's largest installed renewable source of electricity, supplying about 17.4% of total electricity in 2005. Water generates electricity when it drops gravitationally, driving a turbine and generator. While most hydroelectricity is produced by water falling from dams, some is produced by water flowing down rivers (run-of-the-river electricity). Hydroelectricity is ideal for providing peaking power and smoothing intermittent wind and solar resources (Jacobson 2009).

Hydroelectric production, however, is very sensitive to changes in precipitation and river discharge, which is important in conditions of climate change in areas, like some regions in the United States, that derive a significant part of their electricity demand from this source. "For example, every 1% decrease in precipitation results in a 2 to 3% drop in streamflow; every 1% decrease in streamflow in the Colorado River Basin results in a 3% drop in power generation. Such magnifying sensitivities occur because water flows through multiple power plants in a river basin." (Karl et al. 2009, p 59)

As an addendum to the two previous sections, Iceland uses an extraordinary combination of energy resources, enabling it to be 81% self-sufficient in renewable energy: 66% of primary

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[22] Flannery (2009), chapter on "Geothermia".

[23] Wikipedia, "Geothermal heat pump".

energy use from geothermal and 15% from hydropower in 2008 (the remaining 19% was overwhelmingly oil, very little coal). Geothermal energy comes from 27 high-temperature geothermal fields and a large number of low-temperature fields, across the island. In 2008 it was used for space heating (48%), electricity generation (37%), and other purposes (15%). Heating from renewable sources basically used geothermal energy, while hydroelectric power was mainly for electricity generation. An extraordinary high proportion of total electricity usage went into aluminum production. Other renewable energy sources, including wind power, were practically non-existent in Iceland (Eggertson et al., 2009).

Wave energy

The first patents for wave-power devices were issued in the 19th century, and by 1966 the French had built a tidal barrage power station at La Rance River, with an annual production of 600 GWh, which is still operating today (Esteban et al. 2008). Work on wave energy began in earnest only in the early 1970s as a response to the oil crisis. Several government-sponsored programs throughout the world included Japan, Norway and the United Kingdom. These programs advanced the technology considerably and their achievements were impressive, but prototype programs failed to deliver economic supplies of electricity, leaving the technology with a credibility problem that has been hard to overcome.[24]

Winds passing over water create surface waves. The faster the wind speed, the longer the wind is sustained, the greater the distance the wind travels, and the greater the wave height. The power in a wave is generally proportional to the density of water, the square of the height of the wave, and the period of the wave.

Wave power devices capture energy from ocean surface waves to produce electricity. One type of device is a buoy that rises and falls with a wave, creating mechanical energy that is converted to electricity that is sent through an underwater transmission line to shore. Another type is a floating surface-following device, whose up-and-down motion increases the pressure on oil to drive a hydraulic ram to run a hydraulic motor (Jacobson 2009).

Tidal energy

This technology has ancient origins. The earliest evidence of the use of oceanic tides for power conversion dates back to the early Middle Ages and possibly even earlier. Tide mills were specialist water mills driven by the tidal rise and fall. Early tidal power plants utilized naturally-occurring tidal basins by building a barrage (dam) across the opening of the basin and allowing the basin to fill on the rising tide, impounding the water as the tide fell, and then releasing the impounded water through a waterwheel, paddlewheel or similar energy-conversion device. The power was typically used for grinding grains into flour. Power was available for two to three hours, usually twice a day.

Tidal turbines draw energy from currents in much the same way as wind turbines do from air. A generator in a tidal turbine converts kinetic energy to electrical energy, which is transmitted to the shore. The turbine is generally mounted on the sea floor and may or may not extend to the surface. The underwater rotor may be fully exposed to the water or placed

[24] http://www.wave-energy.net/Schools/History.htm.

within a narrowing duct that directs water toward it. Since tides run about six hours in one direction before switching directions for six hours, they are fairly predictable, so tidal turbines are potentially useful base load energy (Jacobson 2009).

The potential for power generation by an individual tidal turbine can be greater than that of similarly rated wind energy turbine. The higher density of water compared to air means that a single generator can provide significant power at low tidal flow velocities, compared with wind speed.

The first commercial-scale modern-era tidal power plant was built in 1965 near St. Malo, France. The tidal barrage at St. Malo uses 24 highly efficient 10-MW turbine generator sets. The barrage has been functioning without missing a tide since being constructed.

The second commercial-scale tidal barrage plant was put into service at Annapolis Royale, Nova Scotia, Canada in 1982. This 16-MW turbine had some teething troubles, but has been functioning without interruption since its early days.

The grandest project of all was the 8,640-MW Severn Tidal Barrage (STB) proposal. A broad range of studies was conducted from 1974 to 1987 on this proposal to dam the Severn Estuary between Wales and England. The tidal range in the Severn is up to 40 feet in places and the potential power from a barrage could provide 12% of the United Kingdom's requirements. Major engineering consultancies, large construction companies, several universities, and the UK Government's Department of Trade and Industry combined to fund and conduct the 13 years of studies costing almost $100 million.

The STB proposal was shelved in 1987 due to "economic problems," but the proposal most likely would have met with fierce opposition from a broad array of environmental groups and local inhabitants. Tidal barrages across inlets or estuaries suffer from four types of environmental problems, which will continue to work against the technology:

1. Barrages block navigation. Locks can be installed to allow some traffic, but it is a slow and costly alternative to free access to the ocean.
2. Barrages impede migration of fish which spawn in fresh water, migrate to salt water, then return after three or four years to spawn and die, drawn to the exact location of their birth. They may pass through the turbines but the mortality rate is about 6%.
3. Barrages change the size and location of the intertidal zone. The alternating wet and dry intertidal zone is unique and only certain types of plants and creatures thrive there. The barrage affects the tidal cycle and changes the water levels, obliging the plant and animal life to adapt to the new location. The functioning of the barrage may be limited to maintain the water at nearly normal levels, but with a high loss of potential output.
4. Barriers change the tidal regime downstream. Canada's Bay of Fundy has the largest tidal ranges in the world and has been the subject of numerous studies of proposed tidal power plant installations. Models of the effects of the huge proposed barrages suggest that the highest tides downstream might be raised as much as nine inches right down to Boston, 800 miles away. Even the possibility of such an impact was considered sufficient

to draw lawsuits from every property owner with a flooded basement from Nova Scotia to Cape Cod.[25]

Fuel cells

Fuel cells link into a long line of hydrogen history going back to the discovery of that element in 1625. The fuel cell was invented by German-Swiss chemist Christian Friedrich Schönbein in 1838 (he discovered and named ozone two years later). Welsh lawyer and scientist Sir William Grove developed a fuel cell between 1839 and 1842, which produced electrical energy by combining hydrogen and oxygen.

The first commercial use of fuel cells was through General Electric (developed by W. Thomas Grubb) in cooperation with NASA and McDonnell Aircraft, leading to its use in Project Gemini in the mid-1960s. In 1959, a 15 kW fuel cell tractor for Allis Chalmers was demonstrated across the United States at state fairs. United Technologies Corporation through its subsidiary UTC Power was the first company to manufacture a large, stationary fuel cell system for use as a co-generation power plant in hospitals, universities, and large office buildings. The company is also the sole supplier of fuel cells to NASA as well as developing fuel cells for automobiles, buses and cell phone towers.

Fuel cells come in at least 20 varieties but they all work in the same general manner. They are made up of three segments which are sandwiched together: the anode, the electrolyte, and the cathode.

At the anode a catalyst oxidizes the fuel, usually hydrogen, turning it into a positively charged ion and a negatively charged electron. The electrolyte is a semi-porous substance designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire creating the electrical current. The ions travel through the electrolyte to the cathode. Once reaching the cathode, the ions are reunited with the electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electrical current is created which can be used to power electrical devices. [26]

Despite its long history, the technology has struggled in the competition with other energy sources and has not reached its full potential. The most promising application according to Goodall (2008) is in providing combined heat and power, one of his "ten technologies to save the planet." He notes that several firms are making good progress in constructing fuel cells for generating electricity and heat on a domestic scale. The advantage of this is that while a pack of fuel cells assembled into a home power plant is about 50% efficient in generating electricity from, say, natural gas, about two-thirds of the heat generated from the plant can be used to heat the home. This means the device can capture 85% of the total energy of the gas, which is better than the capability of a new large-scale gas power station (pp 104-105).

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[25] http://tidalelectric.com/History.htm. Chapter 3 of Esteban et al. (2008) provides a useful and more specific review of ocean energy (tidal and wave).

[26] Wikipedia, 'Fuel cell', most recently accessed March 11, 2010.

Other manufacturers supply larger units, delivering more than 1 MW capable of powering an office block or shopping mail. They also typically convert about 50% of the chemical power of a fuel to electricity, and most of the rest to heat. The implications for urban district heating applications are discussed in the section on energy efficiency.

Biofuels

Biofuels are solid, liquid, or gaseous fuels derived from organic matter, traditionally from dead plants or animal excrement. Wood, grass, and dung are used directly for home heating and cooking in developing countries, and for electric power generation. These technologies have been around for centuries but recent developments dig deeper.

The genesis of biofuels for transportation is associated with two illustrious names. In 1898, Rudolf Diesel premiered the diesel engine at the World Exhibition in Paris to run on peanut oil. Henry Ford was also a key player in the early alternative fuels movement, beginning with his 1908 Model T engine to run on ethanol.[27]

Biofuels include biodiesel and bioethanol (the latter most commonly in blends with gasoline) from agricultural plants and from fermentation of lignocellulose, algae and cyanobacteria. Ethanol is produced in a distillery, usually from sugar cane, sugar beet, molasses, corn, or wheat. Microorganisms and enzymes ferment sugars or starches in these crops to produce ethanol.

The conflict caused by diverting food into energy resources in the United States, Brazil and other countries[28] is being discussed at length as a legitimate concern, but adding other feedstocks and the expansion of industrial biotechnology to replace the petrochemical routes is expected to be very rapid (Villadsen 2007). He advocates parallel research and teaching in the engineering fields that relate to processes where enzymes and living cells are used as "chemical factories". Industrial research using feedstock such as switchgrass, corn stover (leaves and stalks), sugar cane leaves, industrial waste, and algal oil, among others, shows promises of commercial feasibility.

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[27] http://www.nrpw.com/history.html.

[28] Brazil stands out as an apparent exception, due to abundant resources. It has been producing ethanol from sugar cane in increasing quantities since the 1970s, and is the world's leading exporter and demonstrably more efficient than the other large producer, the United States, using mainly corn as feedstock. Production in Brazil grew from 3,989 million US gallons in 2004 to 6,472 million gallons in 2008, from just 1% of the total arable land (Wikipedia article on "ethanol fuel in Brazil", most recently accessed on March 21, 2010). The ethanol program is based on indigenous technology, both industrial and agricultural. It is expected to develop other biomass-derived fuels including ethanol from cellulosic materials and enhanced use of biogas from conversion of waste materials (Goldemberg 2007).

The argument against growing sugar cane for ethanol in Brazil appears to be growing. One reason is that it contributes to deforestation in the Amazon. Though grown in the drier areas of the country, well away from the Amazon, this land use affects the supply and demand of land in the entire country (Goodall 2008, p 167). A $12 billion joint-venture agreement in February 2010 between Royal Dutch Shell and Brazilian sugarcane-to-ethanol producer Cosan is directed squarely towards using biomass for ethanol production. Shell is contributing its equity interests in two advanced biofuel developers, Codexis and Iogen. California-based Codexis is developing biofuel products to use as biocatalysts to convert biomass into fuel. Canada-based Iogen is developing a cellulosic biomass-to-ethanol conversion process that combines thermal, chemical and biochemical techniques, which will enable a wider range of biomass to be converted into fuel (Waltz 2010).

Production of ethanol and biodiesel from agricultural crops has been shown to increase atmospheric emissions of nitrous oxide (N_2O), which is a by-product of nitrogen application in agriculture and a powerful greenhouse gas (Crutzen et al. 2008).

Crops with less nitrogen demand, such as grasses (including sugar cane) or woody coppice species, have more favorable impacts on the climate. Production of ethanol from lignocellulose has the advantage of abundant and diverse raw material compared with sources like corn and cane sugars, but requires a greater amount of collection and processing to make the sugar monomers available to the microorganisms that are typically used to produce ethanol by fermentation. Switchgrass (*Panicum virgatum*) and the perennial grass genus *Miscanthus* are among the major biomass materials being studied today, due to their high productivity per acre.

Costs are coming down dramatically. In the span of less than a decade the enzyme costs of making ethanol from starch has decreased by a factor of at least five, and cost of enzymes (or other bio-based methods for liquefaction of the cellulose) for converting corn leaves and stalks or straw to fermentable sugars has come down by a factor of more than 10. "There is a distinct hope that second-generation ethanol production will become a viable process in the competition with fossil transportation fuels." (Villadsen 2007) The main tools used are either enzyme engineering (improving the action of a specific enzyme) or the genetically engineered modification of a microorganism to improve the productivity of a given desired product.

Algae are proving a potentially useful source of biodiesel. Exxon Mobil's program to improve energy efficiency has until recently concentrated on automotive technology, but in 2009 it announced a plan to invest up to $600 million into algae technology, half of which will fund the research company Synthetic Genomics Inc. Photosynthetic algae such as single-celled "microalgae" and blue-green algae use sunlight to convert CO_2 into cellular oils and some long-chain hydrocarbons that can be processed into fuels and chemicals (DOE 2009b).

Other large petroleum companies are exploring this technology, including Shell investing in a new venture in Hawaii in 2007, where a start-up company is creating large tanks of open-air algae in coastal lagoons for eventual conversion into biodiesel (Goodall 2008, p 203).

Smaller ventures are also starting up, including Aurora Biofuels in Florida, which had operated a pilot plant for 18 months by 2009 and expects to go commercial in 2012 (DOE 2009b). San Francisco-based Solazyme Inc. specializes in algal synthetic biology. In a recent brochure it offers "compelling solutions to increasingly complex issues of fuel scarcity, energy security and environmental impact while fitting cleanly into the pre-existing multi-trillion dollar fuel infrastructure." [29]

Goodall (2008) mentions other ventures and raises the question whether this type of "biofixation" will ever be economically successful on a large scale (p 204). Prospects for this happening are, however, viewed optimistically by the venture capitalists driving the development, and the technology is expanding rapidly supported by continued scientific research, while costs have declined rapidly. Apparent advantages include that it does not

[29] http://www.solazyme.com/. The companies mentioned are examples only; there are many other ventures.

encourage deforestation, nor does it use a large amount of energy for growth and refinement of its products.

Furthermore, the commercial future of small-scale ventures is potentially attractive because it plays straight into the issue of technology diffusion, discussed in the concluding section of this background paper. Dispersion can be into all sort of directions, whether in the developed or the developing world, although the emphasis in our final section is on the latter.

Coal – carbon capture and storage

Carbon capture and storage (CCS) is the diversion of CO_2 from emission sources to underground geological formations (such as saline aquifers, depleted oil and gas fields, and coal seams that cannot be mined), the deep ocean, or as carbonate minerals. It is subject to many government-sponsored investigations including a task force established in February 2010 by the Obama administration works towards a comprehensive federal strategy on CCS (Peridas 2010).

Geological formations worldwide may store up to 2,000 Gt CO_2, which compares with a fossil-fuel emission rate today of an annual rate of about 30 Gt CO_2. To date, CO_2 has been diverted underground following its separation from mined natural gas in several operations and from gasified coal in one case. However, no large power plant currently captures CO_2.

Several options of combining fossil fuel combustion for electricity generation with CCS technologies have been considered, and more are likely to be added given the prominence given to the technology. In one model, integrated gasification combined cycle (IGCC) technology would be used to gasify coal and produce hydrogen. This model (with capture) is not currently feasible due to high costs.

In a more standard model, CCS equipment is added to an existing or new coal-fired power plant. CO_2 is then separated from other gases and injected underground after coal combustion. The remaining gases are emitted to the air.

Other possibilities include injection to the deep ocean and production of carbonate minerals. Ocean storage, however, results in ocean acidification. The dissolved CO_2 in the deep ocean would eventually equilibrate with that in the surface ocean, increasing the back-pressure, expelling CO_2 to the air – unless the CO_2 reacts with calcium (Ca^{++}) to form calcium carbonate ($CaCO_3$). Producing carbonate minerals has a long history. Joseph Black, in 1756, named carbon dioxide ''fixed air'' because it fixed to quicklime (CaO) to form $CaCO_3$. However, the natural process is slow and requires massive amounts of quicklime for large-scale CO_2 reduction. The process can be hastened by increasing temperature and pressure, but this requires additional energy (Jacobson 2009).

The Swedish utility Vattenfall, owned by the Swedish state, is considered a world leader in carbon capture. Starting research in 2001, it began constructing a 30 MW power station as a pilot plant next to its existing coal power station at Schwarze Pumpe in Germany. It began running in September 2008 and is the world's first coal-fired power plant to capture and store its own carbon dioxide emissions (Weiss et al 2008). But learning the lessons from this project will take years. Meanwhile, a larger demonstration plant is planned to start construction in 2010, with the intention to produce electricity by 2015.

Goodall concludes (2008, p 200 and 201): “Two decades is a sobering length of time, particularly since most other large utilities have barely started carbon capture feasibility studies. .. Governments are now beginning to realize that carbon capture offers significant prospects for carbon reduction, but that much research remains to be done.” In short, capturing carbon through CCS at coal and gas power stations is a vital ingredient in any carbon reduction plan, but the technology is not yet sufficiently developed.

This is to put it mildly. "While capturing coal and disposing of it safely is the dream of the coal industry" which "has set up institutes, commissioned experts, lobbied governments and developed a slick marketing campaign to resuscitate the world's reputation of the world's dirtiest form of energy" (Hamilton 2010, pp 159-160), it has already been noted that no coal-fired power plants capture their carbon today, and large numbers of CCS-using plants are unlikely to be built within the next 20 years, and then at very high cost including the necessary comprehensive pipeline system.

Even the American Coalition for Clean Coal Electricity (ACCCE), with a membership of 48 coal and utility companies, has admitted that the commercialization and widespread use of CCS is still 10 to 15 years away – meanwhile, the organization lobbies against the introduction of global warming pollution reductions until the clean coal technology is ready. The Center for American Progress estimates that ACCCE spent at least $45 billion in 2008 to convince Americans that “clean coal” is the solution to climate change, and the coal mining and electric utility industry industries spent over $125 billion in the first nine months of 2008 to lobby Congress (Weiss et al. 2008).

The Center for American Progress also found that the combined profit of the 48 ACCCE members in 2007 was $57 billion, while they invested only $3.5 billion in CCS research in the five years to 2007 (Weiss et al. 2008). A similar reluctance to invest in their own alleged future was noted in Australia which is the nation with most to lose if coal mining was to end. The Australian industry funding for CCS funding is one-thousandth of its revenue, which may be compared with wool growers who allocate 2% of their sales to fund innovation (Hamilton 2010, pp 161-162).

The coal industry wants these systems to be predominantly publicly funded. The following is from the World Coal Institute (2009), an international organization of coal producers and stakeholders: “Current deployment rates for all low-carbon technologies are inadequate to reach government mitigation targets. In particular, current CCS deployment is too slow to allow necessary global GHG emissions reductions goals to be achieved. There is an urgent need to fund demonstration projects and that funding needs to come from both governments as well as a robust carbon market.

While there are a litany of issues that are often cited as barriers to CCS, the private sector cannot proceed with a deployment program on its own. The real barriers to widespread CCS deployment are not technological, they are political and financial.

This report concludes that although responding to global warming is expensive, CCS massively reduces the cost of an effective climate change response. In a post-2012 world, government policies need to include CCS as the costs for deploying CCS are at least comparable to, and in many cases better than, the costs for deploying other low carbon technologies.” (p 3)

For concluding notes on the above discussion, see the section below on “geoengineering as a political crutch”, which debates the penchant in some government and business circles to want to explore large-scale technological “cures” for atmospheric CO_2 pollution. It identifies Hamilton (2010) – and *The Economist* which he quotes – as effectively including CCS technology as another political crutch, an excuse for not going ahead more vigorously with more readily available renewable technologies.

NUCLEAR ENERGY

This group of technologies has received increased attention in recent years as climate change has become recognized as increasingly risky and nuclear energy appears to be solving at least some of its safety, security, and waste management problems. Also, conventional fission technology is no longer the only approach that is being seriously studied – there is significant research into fusion, and into the possible combination of fission and fusion into hybrid reactor technology. While some of these possibilities are not expected to become commercial until the second half of the century, it could happen within the time horizon adopted for this report.

Nuclear fission

Nuclear fission plants produce electricity by splitting heavy elements. As mass is lost in the process, energy is released in accordance with the central mass-equivalence formula in Einstein’s special theory of relativity, $E = mc^2$, where E is energy, m is mass, and c is the speed of light. The energy power of the fission process ($\Delta E = \Delta m \times c^2$) is transferred as kinetic energy to the fission products (such as neutrons).

The most common heavy elements split are uranium-235 (^{235}U) and plutonium-239 (^{239}Pu). When a slow-moving neutron hits ^{235}U, the neutron is absorbed, forming ^{236}U, which splits, for example, into ^{92}Kr, ^{141}Ba, three free neutrons, and gamma rays. When the fragments and the gamma rays collide with water in a reactor, they convert kinetic and electromagnetic energy to heat, boiling the water. The fragments decay further through radioactivity, emitting beta particles (high-speed electrons).

Uranium is stored as small ceramic pellets within metal fuel rods. After 18-24 months of use as a fuel, the useful energy is consumed and the fuel rod becomes radioactive waste that needs to be stored for up to thousands of years. However, with breeder reactors (see below), unused uranium and its product, plutonium, are extracted and reused, greatly extending the lifetime of a given mass of uranium and reducing the waste (Jacobson 2009).

The science of atomic radiation, atomic change and nuclear fission was developed between 1895 and 1945, culminating during World War II when most development was focused on the atomic bomb. After 1945 attention shifted to harnessing the energy in a controlled fashion for naval propulsion and electricity generation. Since 1956 the main interest has been in the technological evolution of reliable nuclear power plants.

Nuclear energy was commercialized in 1959 and subsequent years in a number of countries: France, USA, UK, Canada, and the Soviet Union. From the late 1970s, the industry stagnated with the share of nuclear energy in world electricity production constant at 16-17%. By 2008 the share had fallen to 15% according to World Nuclear Association statistics.[30]

Despite the decline in the share of nuclear energy in the world's electricity production, the WNA is upbeat about the nuclear potential from fission. It notes a renaissance in third-generation reactors to meet projected worldwide electricity demand, particularly in China, India and South Korea. Increasing energy demand, increased dependence on overseas supplies of fossil fuels, awareness of the need for energy security, and the need to limit greenhouse gas emissions, have combined to make a case for increasing use of nuclear power (WNA 2009a, 2009c).

China is embarking upon a six-fold increase in nuclear capacity to 50 GWe (billion watts of electric capacity) by 2020; India's target is to add 20 to 30 new reactors by 2020. A global WNA projection shows at least 1,100 GWe of nuclear capacity by 2060, and possibly up to 3,500 GWe, compared with 373 GWe in 2008.

Breeder reactors generate new fissile material at a greater rate than it consumes such material. The naturally occurring heavy metal thorium is estimated to be three to four times more abundant than uranium in the Earth's crust. These reserves have the potential to power a planet-wide advanced civilization for an indefinite period (Sevior et al. 2010).

Production of fissile material in a breeder reactor is caused by neutron irradiation of fertile material, particularly uranium-238 and thorium-232. Thorium has a single stable isotope, ^{232}Th and is safe, producing only one neutron per fission. In a nuclear reactor this isotope can capture a neutron and be converted to ^{233}U. ^{233}U undergoes fission like ^{235}U and ^{239}Pu. However, when ^{233}U undergoes fission it releases more neutrons than either ^{235}U or ^{239}Pu. It is therefore possible to construct a breeder reactor using thermal neutrons to both generate energy and to breed ^{233}U from thorium, given that sufficient initial quantities of ^{233}U are mixed with ^{232}Th (Sevior et al. 2010).

Concerns over safety and how to store large amounts of nuclear waste appear to be diminishing, and the plans reported above have been put forward despite a rising trend in construction costs for nuclear plants between 1970 and 2000 (corresponding to the period the industry stagnated according to the WNA). It exceeded the cost trends for other large infrastructure projects, such as major gas and coal power stations (Goodall 2008, pp 268-270).

Current nuclear plants are classified "generation II" or "generation III" (all first generation plants have been retired). Thermal and fast generation IV reactors have been under international review since 2002. They are expected to be highly economical with 100-300 times higher energy yields from the same amount of nuclear fuel, to be much safer, to produce nuclear waste that lasts decades rather than millennia, and to be able to consume nuclear waste when producing electricity. Most designs will not be available for commercial

[30] *World nuclear power reactors and uranium requirements as at February 1, 2010* – WNA table viewed March 12, 2010 at http://www.world-nuclear.org/info/reactors.html.

construction before 2030, with the exception of a version of a “Very High Temperature Reactor” called the “Next Generation Nuclear Plant”. It is to be completed by 2021.[31]

In summary, nuclear fission technology appears destined to become more prominent. There is growing agreement that the world is ignoring the technology at its peril. [32] Meanwhile, the nuclear electricity generation’s share in countries that chose a nuclear path is already far in excess of the 15% average, although the shares remained generally static between 1998 and 2008. France led the field in 2008 with 76.2% followed by Lithuania, Slovakia, Belgium, Sweden, Armenia, Switzerland, Hungary, and South Korea. The nuclear share was an above-average 19.7% in the USA, but remained at 2% in China and India. [33]

Nuclear fusion

Nuclear fusion occurs naturally in stars, including our sun. What we see as light and feel as warmth is the result of fusion reaction: hydrogen nuclei collide, *fuse* into heavier helium atoms and release tremendous amounts of energy in the process.

Research into fusion for military purposes began in the early 1940s when scientists on the Manhattan Project investigated it as a method to build a bomb. Fusion was abandoned after concluding that it would require a fission reaction to detonate. It took until 1952 for the first full hydrogen bomb to be detonated, using reactions between the hydrogen isotopes deuterium and tritium. Fusion reactions are much more energetic per unit mass of fuel than fission reactions, but starting the fusion chain reaction is much more difficult. Research into controlled fusion for civilian purposes began in the 1950s, and continues to this day.[34]

The World Nuclear Association notes (2009b): “Fusion power offers the prospect of an almost inexhaustible source of energy for future generations, but it also presents so far insurmountable scientific and engineering challenges.” There are, however, some promising developments which suggest that the technology may become commercial in the late 21st century. This includes the ITER project, which seven participating countries/unions[35] agreed to fund for 30 years in 2006: 10 years covering construction, 20 years for an operating stage. The plant is located in southern France. The plan is to start operating in 2018.[36]

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[31] Wikipedia, ‘Generation IV reactor’, as at March 13, 2010.

[32] NASA’s James Hansen observes that renewable energies such as solar and wind have been gaining in economic competition with coal-fired plants, but would not be able to provide baseload power for years to come. “We should undertake focused research and development programs in next-generation nuclear power” (Dayton 2010). Bill Gates has spoken of five “energy miracles” needed to ensure “innovation to zero” (zero greenhouse gas emissions) by 2050. The five he selected are carbon capture and storage (CCS), nuclear fission, wind power, solar photovoltaic, and solar thermal energy. CCS, he says, is “a tough one”, facing major issues of cost, location of dumps relative to plants, and long-term stability. Nuclear technology faces problems of cost, safety and proliferation, and long-term waste, but “should be worked on.” The wind and solar technologies, facing problems of cost, transmission, and energy storage, are energy farming technologies needing lots of area, and their output is intermittent (Gates 2010).

[33] *Nuclear share figures 1998-2008* (WNA): http://www.world-nuclear.org/info/nshare.html.

[34] Wikipedia, ‘Nuclear fusion’, as at March 13, 2010.

[35] China, the European Union, India, Japan, Korea, Russia, and the USA.

[36] Griffith (2010). ITER was originally known as the International Thermonuclear Experimental Reactor, but the name was dropped in favor of the acronym because of the possible negative connotation of “thermonuclear”.

ITER is based on the "tokamak" concept (a Russian acronym referring to the torus shape of the containing vessel) and is the world's largest of its kind, which it is hoped can be developed to the stage where it is possible to undertake magnetic confinement of the hot plasma. The fuel, a mixture of deuterium and tritium, is heated to temperatures in excess of 150 million degrees Celsius to form the plasma, which is contained in a torus- or doughnut-shaped double-walled vacuum vessel which provides a hermetically sealed plasma container. Strong magnetic fields would be used to keep the plasma away from the walls, produced by superconducting coils surrounding the vessel, and by an electrical current driven through the plasma.[37]

The objective of ITER is to demonstrate fusion as a future energy source, and form a bridge to large-scale production of electrical power and tritium fuel self-sufficiency. DEMO, standing for DEMOnstration Power Plant, is the next step after ITER. A conceptual design could be complete by 2017. If all goes well, DEMO will lead fusion into its industrial era, beginning operations in the 2030s, and putting fusion power into the grid as early as 2040.

"By the last quarter of this century, if ITER and DEMO are successful, our world will enter the Age of Fusion – an age when mankind covers a significant part of its energy needs with an inexhaustible, environmentally benign, and universally available resource." [38]

Hefei, 130 km west of Nanjing and capital of Anhui Province in China, is another significant nuclear research center which is currently taking an interest in hybrid nuclear reactors, discussed in the next section. Three important physics laboratories are located in Hefei including the National Laboratory for Nuclear Fusion (Tokamak) Research under the Institute of Plasma Physics, which is itself under the Chinese Academy of Sciences. [39]

The economist Nicholas Stern (2009, pp 112-113) has advocated that fundamental research priorities for climate change policy should cover a range of largely new and unproven technologies such as "energy storage, which encompasses research into different kinds of batteries (including nano-batteries), into storage through the creation and containment of hydrogen, into storage through lifting or heating of water, and so on. Other priorities include photovoltaics and new materials, new biofuels, enhanced photosynthesis *and nuclear fusion* [our emphasis]. There will be many more."

The timescale of ITER and subsequent nuclear fusion projects fits Arthur's (2009) hypothesis that the development of new bodies of technologies into commercial activities takes decades. If things go well, which they may not, an "age of fusion" may develop in the last quarter of the century. Even a "Manhattan Project" to accelerate the development of nuclear fusion technology may not change this greatly, giving priority to the introduction of nuclear fusion at a commercial scale over technologies that are starting to prove themselves, or could be supported to do so within, say, a decade. Stern's advocacy should be noted, however; he puts nuclear fusion in the same context as photovoltaics and biofuels, which are starting to spark large numbers of projects.

[37] http://www.iter.org/mach/Pages/Tokamak.aspx.

[38] http://www.iter.org/proj/Pages/ITERAndBeyond.aspx.

[39] Wikipedia, 'Hefei', as at March 25, 2010.

Hybrid fusion reactors

One problem with fusion is the size of the reactor core. To make a fusion reactor self-sustaining requires a plasma volume of about 3,300 m^3, more than three times the proposed volume of ITER. Another major unsolved problem is constructing a reactor wall capable of withstanding the intense bombardment of high-energy neutrons generated by the plasma. Hybrid nuclear power potentially solves both these problems by reducing the required size of the plasma volume and by reducing, by a factor of 50, the energy flux reaching the outer reactor wall (Hunt and O'Connor 2010).

Hybrid nuclear power has been discussed for decades (references in Kotschenreuther et al. 2009) but has not yet been explained to governments, industry, researchers, and the public. Combining the two forms of nuclear power, fission and fusion, in a single reactor minimizes the environmental impact, reduces risks, enlarges reserves of nuclear fuel, and is more flexible to operate (Hunt and O'Connor 2010). It also eliminates some of the waste problems of the nuclear industry and potentially helps rid the world of plutonium and other weapons-grade materials (Kotschenreuther et al. 2009).

Several research institutions are actively engaged in research into hybrid fusion technology, including the ITER participants, the Institute of Fusion Studies of the University of Texas at Austin, and the Institute of Plasma Physics in Hefei, China.

Conclusion: nuclear energy

In conclusion, nuclear power, from fission and potentially from fusion or using hybrid fusion reactors, is almost certainly destined to become prominent in combating increasingly serious climate change, though only fission has yet become technically and commercially viable.[40]

GEOENGINEERING

The inclusion of this topic recognizes a range of possible technologies with a different status from those discussed above. The definition of geoengineering adopted in this report provides a *possible* fallback position for particular circumstances arising in the future. It should be more a matter of "What can we do if things start to get really wrong?" than trying

[40] A general note of caution is appropriate here: Burgeoning technological development in any field is bound to lead to a wealth of more or less soundly based business ventures which will be vigorously promoted, whether they relate to nuclear science or other new energy applications. What follows is just one example which may, or may not, prove to have real economic and technical potential. The informative and inspiring role that investment advisers play, and have a right to play, is acknowledged but naturally not all their information leads to commercial ventures.

In March 2010, the Internet was abuzz with advice on "the most profitable nuclear advancement in 50 years," in which "over the next six months, thanks to the unprecedented discovery of a "monster metal", one company is about to create a global energy monopoly." (http://www.angelnexus.com/o/web/19676?lloct=2). The "metal" is the white crystalline beryllium oxide (BeO), the thermal conductivity and melting point of which are both very high (http://en.wikipedia.org/wiki/Beryllium_oxide), whereas the common fuel used in nuclear fission reactors, uranium dioxide (UO_2), has low thermal conductivity which leads to a variety of fuel performance problems. The background is that nuclear engineers from Purdue University undertook an investigation of enhanced thermal conductivity oxide fuels, which involved mixing BeO with UO_2 (Latta et al. 2008). The research received funding from the Department of Energy as far back as 2002, and BeO has been used in nuclear applications since the dawn of postwar civilian nuclear research in 1945 (Solomon et al. 2006). A world monopoly of the oxide would be hard to achieve, judging from this information.

to visualize it as a possible alternative in its own right any time soon. The definition adopted for geoengineering covers solutions requiring a radical change in the adoption of climate change technology, and being outside or close to the boundaries of the plausible within the confines of the 21st century, and therefore largely outside the scenario-planning approach.

The scenario stories describe what would happen without mitigation, regardless of global temperatures and other consequences. Mitigation could conceivably include adopting a geoengineering technology to avoid entering decades of global economic decline.

The Royal Society in a report on the science, governance and uncertainty of geoengineering (Shepherd et al. 2009) distinguishes two main groups:

- Carbon dioxide removal (CDR) techniques remove CO_2 from the atmosphere, including land and coastal management methods treated as mainstream, rather than radical, technologies in this paper. One CDR technology fitting our definition of geoengineering as a radical potential solution is ocean fertilization, which the Royal Society report says carries a high risk of unintended and undesirable ecological side effects (p 18). The report sees no potential for large-scale carbon dioxide scrubbers, which trap CO_2 from the air. [41] It is more upbeat about geoengineering proposals aimed at increasing the ability of the Earth's carbonate or silicate minerals to decrease emissions and atmospheric concentrations of CO_2. It sees the primary barriers to deployment as related to scale, cost, and possible environmental consequences (p 13).
- Solar radiation management (SRM) technologies aim at reflecting a small percentage of the sun's light and heat back into space. Possible techniques include increasing the albedo or reflectivity of (a) Earth's surface, (b) oceanic clouds, and (c) the stratosphere. Another possible technique is to reduce incoming solar irradiance through space-based installations, which as discussed below this is likely to remain prohibitively expensive.

The Royal Society's headline message (Shepherd et al. 2009, p ix) is clear: "The safest and most predictable method of moderating climate change is to take early and effective action to reduce emissions of greenhouse gases. No geoengineering method can provide an easy or readily acceptable alternative solution to the problem of climate change."

Some geoengineering methods are deemed potentially useful in future to augment continuing efforts to mitigate climate change by reducing emissions, and are "very likely to be technically possible. However, the technology to do so is barely formed, and there are major uncertainties regarding its effectiveness, costs, and environmental impacts."

Geoengineering versus nuclear options

The geoengineering options should be compared with the potential for fusion-based energy production. As outlined in the section on nuclear fusion, the technology remains difficult but projects are underway, including the DEMOnstration project planned to follow the current ITER project in the latter part of the 2010s. If this is successful, nuclear fusion could become

[41] A variety of scrubber called "artificial trees" has been advocated as a potentially lower-cost method of removing CO_2 from the air passing it over a substance such as sodium hydroxide, so that it combines with the chemical and can then be removed and stored underground. It is reported as being low-risk, potentially highly effective, and moderate to high cost, but a prototype is still five years away (Giles 2010).

a commercial reality sometime toward the end of the century. Hybrid fusion reactors may help pave the way for the technology.

The Royal Society report clearly considers that nuclear technology to be distinct from its subject of geoengineering solutions to climate change, and nowhere attempts to compare the two. Arguably, however, the potential of nuclear technology, including straight or hybrid fusion, is greater than any geoengineering option, at lower risk and probably at lower cost.

Geoengineering politics

Geoengineering has been defined as intentionally large manipulation of the natural global environment. It refers to technologies being proposed by some scientists and commercial journalists as a "politically realistic" remedy for climate change (Hall 2005). Governments tend to see it as a means of overcoming the problem of replacing fossil with renewable technology to reduce greenhouse gas emissions – a feeling temporarily reinforced by a disappointing outcome of the Copenhagen climate conference in December 2009. Despite the fact that most or all geoengineering technologies remain commercially unproven, the danger is that the assessment of some potentially massive environmental risks will be allowed to take a back seat to political convenience – even to the extent of postponing other action against climate change because "geoengineering will fix it". This is further discussed in the section below, called "geoengineering as a political crutch."

In September 2001, President Bush's Climate Change Technology Program convened a meeting to discuss "response options to rapid or severe climate change". Despite the fact that administration officials were then insisting publicly that there was no firm proof that the planet was warming, they were actually exploring potential ways to turn down the heat.

Reliance on a "technological fix" has permeated much political thinking, and it remains in the political line of sight, sufficient in March 2010 for the bipartisan US National Commission on Energy Policy to create a high-level task force to examine research and policy issues associated with geoengineering (Mandel 2010).

Robert Socolow, known for the "stabilization wedges" described in a previous section of this background paper, has issued a warning to be "very careful" when it comes to thrashing out guidelines for the "nascent field of geoengineering" (Tollefson 2010). Socolow highlighted the legal, moral and ethical quandaries of geoengineering to a research conference at the Asilomar Conference Center near Monterey, CA, in March 2010. Symbolically, the conference was held in the same location as a landmark conference in 1975 on the then budding field of genetic engineering – then regarded as frightening but since developing as a pivotal part of the burgeoning field of biotechnology.[42]

While participants generally agreed on the need to identify a responsible way ahead for geoengineering research, Socolow's cautionary note was clearly heeded according to Jeff Tollefson, the *Nature* journal reporter. One participant said, "We're scared, and nothing

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[42] There is another possibility if we look another 30-35 years ahead. In a best-case scenario, biotechnology coupled with other technologies may have made decisive and economically efficient contributions towards the twin global problems of poverty and climate change. Geoengineering solutions, meanwhile, may still be regarded as too expensive and/or too environmentally risky.

brings people together like fear." Tollefson concluded: "It was evident from the beginning that the much broader field of geoengineering would not yield to simple principles as quickly as had genetics." The 2010 conference failed to come up with clear guidelines for geoengineering experiments.

In the United Kingdom, a memorandum of draft principles for the conduct of geoengineering research has been submitted to the Parliament (Rayner et al., 2009). Known as the "Oxford Principles" because the lead author and two of the four co-authors work there, it proposes five principles for the guidance of geoengineering research:

1. *Geoengineering to be regulated as a public good*: While private sector involvement in the delivery of a geoengineering technique should not be prohibited, and may even be encouraged in the interest of timeliness and efficiency, regulation of such techniques should be undertaken in the public interest at national and/or international level.
2. *Public participation in geoengineering decision-making*: Wherever possible, those conducting geoengineering research should be required to notify, consult, and ideally obtain the prior informed consent of, those affected by the research activities. Capturing carbon dioxide from the air and sequestering it geologically within the territory of a single state will probably require consultation and agreement only at the national or local level. A technique which involves changing the albedo of the planet by injecting aerosols into the stratosphere will most likely require global agreement.
3. *Disclosure of geoengineering research and open publication of results*: There should be complete disclosure of research plans and open publication of results to facilitate better understanding of the risks and to reassure the public as to the integrity of the process. It is essential that the results of all research, including negative results, be made publicly available.
4. *Independent assessment of impacts*: An assessment of the impacts of geoengineering research should be conducted by a body independent of those undertaking the research; such assessment should be carried out through the appropriate regional and/or international bodies if extending beyond boundaries. Assessments should address both the environmental and socio-economic impacts of research, including mitigating the risks of lock-in to particular technologies or vested interests.
5. *Governance before deployment*: Any decisions with respect to deployment should only be taken with robust governance structures already in place, using existing rules and institutions wherever possible.

These recommendations would appear to be the first submitted to a national political body and will undoubtedly be modified, including strengthening or weakening provisions that currently read somewhat loosely, as in expressions like "should", "wherever possible", "ideally" and other phrases that seem to play into the hands of a political process. Socolow's warning should be kept in mind in all contexts, including big business.

In January 2006, Australia, China, India, Japan, Korea, and the United States signed the Asia-Pacific Partnership on Clean Development and Climate. [43] At the time, Australia and the US were the only major countries that hadn't ratified the Kyoto Protocol, and the leaders of both countries publicly declared their faith in "technology" while remaining climate skeptics. The technology President Bush and then Prime Minister John Howard of Australia ended up espousing was carbon capture and sequestration (CCS), one part of the Royal Society's carbon dioxide removal (CDR) group which may no longer be considered "geoengineering" but has not yet proven itself as a large-scale technical solution.

At the September 2001 meeting of the Bush Climate Change Technology Program, the proposals included the following six technologies, rated for feasibility, cost, and risk in an anonymously written *Popular Science* article (Anon 2005). Some of these technologies were never serious contenders but give an idea of the range of options considered:

- Underground storage of carbon dioxide, rated 10 out of 10 for feasibility (the Weyburn project already exists in Saskatchewan, Canada), moderate on cost, and 4 on risk. The proposal differs from the coal-CCS technology. The CO_2 in question here is used in high-pressure form in an oil field to drive the oil to the surface. The risk is stated to be seepage of the carbon dioxide from its highly pressured state underground.
- Turning CO_2 into rock: feasibility 7, cost moderate, risk 3. Since the *Popular Science* article in 2005, the CarbFix experiment has started at Hellisheidi, Iceland, fixing CO_2 in basalt using that nation's abundant geothermal power. The limitation is that the feedstock and CO_2 must be heated to high temperatures.[44]
- Wind scrubbers to filter carbon dioxide from the air: feasibility 4, cost high, risk 4 – the Royal Society report (Shepherd et al. 2009) might rate it even lower. Giant porous filters would act like flypaper, trapping CO_2 molecules to be bound with sodium hydroxide or calcium hydroxide-chemicals that would be pumped through the filters. The CO_2 would then be stripped from the binding chemical, and sequestered.
- "Fertilization" of oceans with iron to encourage growth of plankton, again given the thumbs down by Shepherd et al. (2009), especially on risk: Feasibility 10 (pilot project already carried out, with spectacular impact on plankton growth), cost low, risk 9. The risk is very high because the resulting plankton blooms, in addition to gorging on CO_2, may devour other nutrients. Deep currents carry nutrient-rich water from the Southern Ocean northward to regions where fish rely on the nutrients to survive.

  The Royal Society report also mentions other "fertilization" techniques, such as increasing the phosphorus and nitrogen content of the oceans, but again the risk is seen as high (Shepherd et al. 2009, p. 18).

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[43] Canada joined in 2007 as a seventh member. The organization is still formally in place.

[44] The project participants comment (http://www.or.is/English/Projects/CarbFix/AbouttheProject/): "It shall be kept in mind that the amount of pores in the basaltic rock is limited. Therefore, the results from the Hellisheidi experiment will not save the world's climate. However, the experiment might demonstrate that a "near zero CO_2 emission" geothermal power plant is a possibility and even the option to store the main part of Iceland's CO_2 emission in a safe way. This technology, if proved successful, can then be exported to other basaltic terrains of the Earth." In the absence of geothermal sources, however, the technology is less likely to result in a net reduction of atmospheric CO_2, using fossil fuel in the heating process.

The recent UNEP report on *Blue Carbon* (binding carbon in the oceans) comes to similar conclusions (Nellemann et al. 2009). “With too many unknown variables and current modeling limitations, assessment of the risks and consequences of these proposals will be a challenge. .. Current research shows that most ocean geo-engineering concepts are high risk for undesirable side-effects (e.g. increase in ocean acidification), have limited application, uncertain outcome and potentially non-reversible impacts on the marine environment. This highlights the need to apply a precautionary approach when investigating ocean geo-engineering interventions.” (p 41)

- Improving the ability of clouds to reflect sunlight back into space: feasibility 6, cost moderate, risk 7. The proposal is to seed clouds with tiny salt particles to enable more droplets to form – making the clouds whiter and therefore more reflective. The high risk assessment reflects concern that although the tiny salt particles released by evaporating sea mist are perfect for marine stratocumulus-cloud formation, they are too small to create rain clouds. It might make it harder for rain to form.
- Deflection of sunlight from the Earth through the use of a giant space mirror “spanning 600,000 square miles”: feasibility rated extremely low at 1, cost extremely high, risk 5. In 1989, James Early of the Lawrence Livermore National Laboratory proposed deflecting a measure of sunlight with a "space shade" located at Lagrangian Point *L1* – an orbit 1.5 million kilometers up, where Earth's gravity and that of the Sun are balanced so an object can remain stationary relative to both bodies. The low rating on feasibility and the high cost suggest that this option is doomed in the foreseeable future. It would weigh about 100 megatons under Earth's gravity. As for assembling his giant mirror and placing it at L1, Early suggested using moon rock for the materials and building a manufacturing plant on the lunar surface, then launching the components by a mass driver from the Moon to L1 (Williams 2007).[45]

Looking at the six options listed above, there would seem to be little chance for any of them to become worldwide solutions in this century. The first two are not really geoengineering options in the sense that they represent even potentially large-scale manipulations of the global environment, but they could have some limited applications in suitable positions as the leaders of the Icelandic project suggest.

The four other options fall squarely in the area of geoengineering, options relying on “big fixes”. They carry heavy environmental risks (especially the plankton option), or are

[45] Roger Angel, University of Arizona Professor and the Steward Observatory Mirror Laboratory's director, has offered another plan: to place in orbit at L1 a very great number of small, already assembled objects. Angel's plan calls for small "flyers": transparent sheets two feet in diameter and 1/5,000 of an inch thick, each weighing approximately one gram under Earth's gravity. Trillions of these objects, according to Angel, could together form a cylindrical cloud having a diameter half that of Earth's and a length of 60,000 miles. Interposed lengthwise between the Sun and Earth at L1, this cloud would uniformly reduce sunlight on our planet's surface by 2%, which would be sufficient to offset the warming produced by even a doubling of atmospheric carbon dioxide. Angel estimates that the total mass of all the flyers composing his cloud would be 20 million tons and a total of 20 electromagnetic launchers. At $10,000 a pound, conventional rockets would be a prohibitively expensive way of getting that much mass into orbit. Human beings would have to launch a stack of flyers every five minutes for 10 years to put the whole structure in place. Angel stresses that his plan is an emergency option, for use only if climate change so accelerates that global catastrophe looms within a decade or two. It is, he says, "no substitute for developing renewable energy, the only permanent solution." (Williams 2007).

prohibitively expensive and in a 21st century context technically impossible in view of the size and weight of the mirror and how and where it would be placed at L1. The last option to be discussed, however, is a geoengineering idea which has gained prominence under the influence of a distinguished main supporter, after three decades of theoretical debate.

Particles into the Stratosphere

Stephen Schneider (1996) relates how the geoengineering concept by the mid-1990s was maturing from a somewhat wild past: “Schemes to modify large-scale environment systems or to control climate have been seriously proposed for over 50 years, some to (1) increase temperatures in high latitudes [*sic*], (2) increase precipitation, (3) decrease sea-ice [*sic*], (4) create irrigation opportunities or to offset potential global warming by spreading dust in the stratosphere to reflect away an equivalent amount of solar energy.” (p 291).

The last item is what concerns us here. The originator of the idea was Russian climatologist Mikhail Bodyko (1977), proposing a stratospheric particle layer to reflect away enough sunlight to offset greenhouse warming (Schneider 1996, p 293).

The National Academy of Sciences brought it into the debate in a 1992 report on the policy implications of climate change. Stephen Schneider, as a panelist, “reluctantly” voted in favor of retaining the chapter on geoengineering in the report, which centered on the stratospheric option. The majority of panelists felt that humanity is already involved in a large project of inadvertent “geoengineering” by altering atmospheric chemistry, and that engineered countermeasures need to be evaluated but should not be implemented without broad understanding of the direct effects and the potential side effects, ethical issues, and risks (Schneider 1996, p 296).

Edward Teller, the nuclear physicist famously linked to the hydrogen bomb, supported the idea despite being doubtful that climate change even existed. “It's wonderful to think that the world is so very wealthy that a single nation – America – can consider spending $100 billion a year on a problem that may not exist.” “Let us play to our uniquely American strengths in innovation and technology, offsetting any global warming by the least costly means possible.” “Injecting sunlight-scattering particles into the stratosphere appears to be a promising approach. Why not do that?” (Teller 1998)

Nobel Prize-winning Dutch chemist Paul Crutzen brought the idea to the fore. In an editorial essay in the journal *Climatic Change* (2006) he noted that CO_2 emissions from fossil fuel burning is partly offset by the cooling effect of sulfur dioxide particles, but at a high price because the pollution particles affect health and lead to more than 500,000 premature deaths per year worldwide. Furthermore, global SO_2 emissions and thus sulfate loading have been declining at the rate of 2.7% per year, potentially explaining the observed reverse from dimming to brightening in surface solar radiation noted in Hoegh-Guldberg (2010a).[46]

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[46] Sulfur is not the only proposed material. Gregory Benford suggests that the particles could be composed of diatomaceous earth. "That's silicon dioxide, which is chemically inert, cheap as earth, and readily crushable to the size we want," he says according to Williams (2007). Williams also quotes Stanford University climate scientist Ken Caldeira: “It appears as if any small particle would do the trick in the necessary quantities. I've done a number of computer simulations of what the climate response would be of reflecting sunlight, and all of them

Crutzen noted that his idea is not new, but no one had previously linked climate cooling and improved health. Among possible negative side effects, the impact on stratospheric ozone came to his mind first. However, he found that the impact on the ozone layer would be minor compared with major volcanic eruptions like that of Mount Pinatubo in the Philippines in 1991.[47]

The Royal Society report (Shepherd et al. 2009, p xiii) noted: "Of the Solar Radiation Management methods considered, stratospheric aerosols are currently the most promising because their effects would be more uniformly distributed than for localized Solar Radiation Management methods, they could be much more readily implemented than space-based methods, and would take effect rapidly (within a year or two of deployment)."

There may, however, "be serious consequences should geoengineering fail or be stopped abruptly. Such a scenario could lead to very rapid climate change, with warming rates up to 20 times greater than present-day rates. This warming rebound would be larger and more sustained should climate sensitivity prove to be higher than expected. Thus, employing geoengineering schemes with continued carbon emissions could lead to severe risks for the global climate system." (Matthews and Caldeira 2007, p 9949). Shepherd et al. (2009, p 24) note that "it cannot be foreseen whether or not such a rapid cessation might ever occur, or under what circumstances." In any case, the Royal Society report favors mitigation over any radical geoengineering solution.

Geoengineering as a political crutch

Australian academic Clive Hamilton's latest book is deeply pessimistic, so much so that he calls it *Requiem for a Species* (Hamilton 2010). It starts from similar ground as our background papers, especially Hoegh-Guldberg (2010a and b), but it has chapters on "growth fetishism," consumerism, "many forms of denial" and "disconnection from nature," which springs naturally from the author's specialty of public ethics. While the main purpose for the Florida Keys project has been to provide perspective for the four scenario stories (assuming they remain equally plausible), Hamilton concludes that "it is too late to prevent far-reaching changes in the Earth's climate", and "those who want to argue that I am too pessimistic must explain where the analysis goes wrong." (p xiii) The general view, judging from the literature, is that the situation is serious but there is still room for a reversal, given appropriate action. Hamilton is right, however, in stressing the severity of the situation, and his book should be read widely.

Hamilton calls his Chapter 6 "Is there a way out?" (pp 159 ff). He points to three technologies that might seem to offer hope: carbon capture and storage (already discussed in an earlier section including Hamilton's comments), renewables and nuclear power, and

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indicate that it would work quite well. I wouldn't look to these geoengineering schemes as part of normal policy response, but if bad things start to happen quickly, then people will demand something be done quickly."

[47] Also, as noted by NASA and others, the Antarctic ozone hole was healing following the international regulation of chlorofluorocarbon (CFC) gases through the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (http://ozonewatch.gsfc.nasa.gov/facts/hole.html). This was coupled with complex other factors related to aerosols indicating multitudinous feedbacks leading to the conclusion of one research team that the scientific understanding of climate and other drivers, interactions, and impacts remains very low. This includes a probable positive relationship between ozone hole healing and a warming climate (Carslaw et al. 2010).

geoengineering. On CCS, he endorses *The Economist*, writing on March 5, 2009 on 'The illusion of clean coal': "CCS is not just a potential waste of money. It might also create a false sense of security about climate change, while depriving potentially cheaper methods of cutting emissions of cash and attention – all for the sake of placating the coal lobby."

Basically dismissing a revival of nuclear power as too slow to implement (he is not against it in principle), he notes under the heading of "wind, sun and atom" (p 173): "An emergency response over the decade to 2020 based on a huge effort to shift from fossil fuels to energy efficiency, renewable energy and natural gas is certainly feasible technically. It could also be achieved at reasonable economic cost. This is not to say it would be painless. .. Sadly, the national and international political institutions that must bring about the changes are too slow, too compromised and too dominated by old thinking to mandate the energy revolution we must have to guarantee our survival."

This leaves geoengineering or "climate engineering" as a potentially dangerous crutch. Hamilton puts is as follows (pp 185-186): "Fossil fuel corporations are currently unwilling to support geoengineering in public for fear of being accused of shirking their responsibilities, but once the approach becomes part of the mainstream debate and gains political traction we can expect to see the commitment to cut greenhouse gases diluted. The promise of geoengineering is the perfect excuse for decades of delay. If, as the Stern report says, climate change is the biggest market failure we have ever faced, geoengineering is the most serious *moral hazard* we have ever faced." (Our emphasis)

The reference to "moral hazard" is important and needs explanation. The Royal Society report on geoengineering (Shepherd et al. 2009, p 37) states: "The very discussion of geoengineering is controversial in some quarters because of a concern that it may weaken conventional mitigation efforts, or be seen as a 'get out of jail free' card by policy makers. .. This is referred to as the 'moral hazard' argument, a term derived from insurance, and arises where a newly-insured party is more inclined to undertake risky behavior than previously because compensation is available. In the context of geoengineering, the risk is that major efforts in geoengineering may lead to a reduction of effort in mitigation and/or adaptation because of a premature conviction that geoengineering has provided 'insurance' against climate change."

The Royal Society clearly prefers mitigation to geoengineering, for reasons both of justice and the moral hazard argument against it (p 39). But the authors conclude that the moral hazard argument requires further investigation to establish how important an issue this should be for decision-makers (p 45). As his reference to geoengineering as an unprecedented moral hazard shows, Hamilton is concerned that this inconclusive finding may encourage vested interests to push it at the expense of other climate control measures.

In conclusion, Hamilton reinforces our own strong impression that these radical technologies should not be given priority over the other approaches discussed in this paper. The way to combat climate change is not to manipulate nature but to realize that human systems must be subordinated within the possible to avoid wrecking the natural environment any more than has happened to date. The vast majority of climate scientists agree on this. So does Graeme Taylor in *Evolution's Edge* (2008) with the requirement that "the paradigm must be flipped" to fit economics and business within the capacity of the natural environment rather than the other way round which currently prevails (Hoegh-Guldberg 2010a).

Geoengineering and the four scenarios

A common feature among those debating large-scale geoengineering options, including Crutzen (2006), the scientists quoted by Williams (2007), and Shepherd et al. (2009), is that they all regard these technologies as possible fallback options, and would much rather see greenhouse gas emissions reduced through conversion to renewable fuels, better energy efficiency, and reforestation. But they have generally taken a pessimistic view of the political and economic will to take action. Gregory Benford of the University of California put it bluntly (as quoted by Williams 2007):

"The political impossibility of what I call the prohibitionist agenda – that is, carbon prohibitionism – brings a kind of hallucinogenic quality to the global-warming discussion. No economist I know believes that global carbon emissions can be restrained within a century to even the level we have now. Every economist knows that the timescale for changing energy infrastructure is at least half a century to a century, just because of replacement costs. Economists are scientists too, and ignoring them isn't just blind: it's perverse."

This may explain why he and others have become proponents of large-scale geoengineering fallback options, but it reveals either ignorance or rejection of the emerging discipline of climate change economics, and the rising impact of Chinese green technologies which could have a profound influence on future climate change agreements (see further Hoegh-Guldberg 2010c).

As far as the scenarios are concerned, it was stated in the introduction to this section that geoengineering may be attempted some time in future, but mitigation including such attempts is not part of the basic storylines. The scenarios are to be allowed to run their course to demonstrate the consequences.

ENERGY EFFICIENCY MEASURES

Ten technologies to save the planet (Goodall 2008) noted only one technology (or domain of technologies) making the list under the heading of energy efficiency: "super-efficient homes", epitomized by the "Passivhaus" (passive house), four townhouses built in Darmstadt, Germany in 1990-91. Another of Goodall's ten technologies, distance heating, was linked to fuel cells but really represents another way to use energy more efficiently. The last heading in this section shows a small selection of the numerous other ways that exist to improve energy efficiency. Building applications have proven most spectacular, but the mass of individual energy efficiency applications adds to a potentially huge total contribution.

The passive house

The idea germinated from a conversation in May 1988 between Professors Bo Adamson of Lund University, Sweden, and Wolfgang Feist of the Institute for Housing and the

Environment in Darmstadt.[48] Thanks to efficient insulation and clever design, the houses did not need a conventional central heating system, nor would they need air-conditioners for the summer. Goodall lists the key features: architectural design and construction, passive solar design, super-insulation, advanced window technology, airtightness, mechanical ventilation systems with heat recovery, and recovering the waste heat from lighting, appliances, and human and animal bodies. He notes (p 119):

"Heating and cooling don't get quite the same media attention in the climate-change debate as cars and electricity-hungry gadgets. But they should. If you added up the emissions of all the world's gas and oil boilers, coal fires, electric heaters and air-conditioning units, then you'd probably find that managing the temperature of buildings – either through heating or air-conditioning – is the world's single most climate-damaging activity."

There are now an estimated 15-20,000 passive houses in the world, mainly in Germany and Scandinavia. The first passive house in North America was built in Urbana, Illinois, in 2003 to demonstrate that the stringent passive house energy standards could be met in the severe climate of Central Illinois, as much as in Scandinavia .[49]

Goodall (2008, p 142) concluded that the technologies for improving the energy consumption of domestic housing are simple and relatively well understood, to a large extent because of the work of Wolfgang Feist and the Darmstadt institute. Insulation and airtightness are key factors. So far, however, developed countries have been slow to see the potential.

Distance heating

District heating was developed many decades ago to offer households a relatively cheap way of obtaining heat in winter, long before climate change became an issue. The first modern systems were built in the US the 1880s and in Europe in a number of German cities in the 1920s (Ericsson 2009). In Denmark, the first local district heating associations also go back to the 1920s.[50] Today, 60% of Danish households benefit from district heating, of which 75% comes from central and regional power stations.[51] Other European countries with a high proportion of residential and non-industrial premises served by district heating include Iceland (95%, using the abundant geothermal energy available there), Estonia (52%), Poland

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[48] Wikipedia (Passive House, as at October 2009). The institute is owned by the State of Hessen and the City of Darmstadt.

[49] The designer was German-born Katrin Klingenberg, who applied several of the many techniques, systems and materials that can be used to reduce energy load by the required 90%. Among them: super-insulation and a super-tight thermal envelope, orientation that maximizes passive solar heating in winter and cooling in summer, triple-glazed windows, a 100-foot long earth-tube air intake for pre-heating and –cooling, heat recovery ventilation that recovers heat from exhaust air and ensures constant outdoor air ventilation for excellent indoor air quality, and instantaneous electric water heating. (http://www.e-colab.org/ecolab/SmithHouse.html).

[50] http://www.danskfjernvarme.dk/

[51] http://www.danskenergi.dk/EnergiITal/Elforsyning.aspx.

(52%), Sweden[52] (50%), Finland (49%), and Slovakia (40%). These high rates contrast with Germany (12%), the Netherlands (3%), and the United Kingdom (1%). [53]

District heat and power schemes supply entire urban areas, as distinct from fuel cells which may be scaled up to power and heat large buildings. A centrally located heating plant, often fueled by local wood, provides the heat for the surrounding households. Increasingly, however, district heating plants are being used to generate electricity as well as heat, as has long been the case in Denmark. Most Danish plants are still powered by gas and other fossil fuels, but about 40% of the heat produced is CO_2-neutral, because the plant has burned renewable wood or domestic waste. However, substantial issues remain because there are other ways of using organic materials, notably to produce either cellulosic ethanol or biochar (Goodall 2008, pp 113-118).

Other energy efficiency ideas

Despite Goodall's rejection of other energy efficiency measures in his list of ten technologies, there are numerous opportunities, and his remark (p 271) on the limited impact of energy-efficient home appliances overlooks the value of promoting and marketing these efficiencies – constantly making people conscious of the importance of energy efficiency across a wide range of products and services.

One well-known book from the 1990s is *Factor Four* (Weizsäcker et al. 1997) by the founder and former president of the Wuppertal Institute for Climate, Environment and Energy in Germany, Ernst von Weizsäcker, and resource analysts Hunter and Amory Lovins who founded the Rocky Mountains Institute in Snowmass, Colorado in 1982. The book sets out to demonstrate that resource productivity can grow fourfold; we can live twice as well, yet use only half as much.

Part One gives "fifty examples of quadrupling resource productivity" through energy, material, and transport productivity. They demonstrate the potential and scope for applying energy efficiency measures:

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[52] Sweden provides a good example of the important role district heating systems can play an in increasing the use of renewable fuel sources for heating purposes, as well as reducing total primary energy demand (Ericsson 2009). The economies of scale of district heating systems provide an opportunity of using deep geothermal heat as well as unrefined biomass such as waste wood, straw, and forestry residues, and municipal solid waste. The Swedish example also shows how quickly the feedstock composition can change.

Until 1980 Swedish distance heating relied almost completely on oil. In the 1980s oil was replaced by solid fuels including biomass, peat, municipal solid waste, and especially coal. Electric boilers and large geothermal heat pumps also began to be installed in this period. In 1985 natural gas was introduced in Sweden and entered distance heating production. In the 1990s many of the coal-fired plants were converted to biomass which expanded considerably and has continued to do so ever since. Apart from the biomass expansion in the 2000s the use of municipal solid waste has been greatly increased, and electric boilers have been nearly phased out.

The biomass use consists mainly of wood fuels (44% of the total energy supply in 2007), such as forestry residues and waste products such as demolition wood and loading pallets, and wood pellets. The remaining biomass is mainly tall oil, a by-product of pulp production. The biomass has for the past 10-15 years included both imported fuels as a result of the high biomass demand in Sweden compared to that in other countries. The biomass imports include wood fuels from the Baltic countries, wood pellets from Canada, and waste wood and other waste from Germany and the Netherlands. The imports from Canada have been criticized as running counter to the principle of minimizing the environmental footprint through distance heating.

[53] Wikipedia: District heating, accessed October 2009.

- Building design: The Darmstadt “Passivhaus”; space-cooling in hot-climate houses in California; super-windows and large-office retrofits; renovating old housing stock using super-insulating finishing material.
- Exploiting a huge potential for improving air-conditioning technology in six simple steps: keeping unwanted heat out of the building; expanding the “comfort envelope” using office chairs with mesh seats that ventilate the body, super-windows, ceiling fans etc.; passive cooling removing unwanted heat through the normal functioning of the building itself, without special equipment; cooling alternatives to air-conditioning; improvements to conventional air-conditioning; better controls and software for other energy use.
- Appliances and office equipment: More efficient refrigerators, refrigerator-freezers, washing machines, dishwashers, clothes dryers, electric cooking equipment, heat pumping, and ventilation; incandescent lamps, tubular fluorescent lamps, and lighting design; computers moving to laptop size; design synergies including power supply; more efficient printers, fax machines and photocopiers; reducing the number of solar panels drastically by converting from AC to DC; using low-voltage DC for other domestic use.
- Better application of engineering principles: Applying common sense, whole-system engineering, healthy skepticism about traditional practice and rigorous application of accepted engineering principles.
- Achieving better energy efficiency of power generation: More efficient new-generation power stations using combined-cycle gas turbines; adding combined heat and power and optimized gas boilers.
- Better material productivity based on material inputs per service unit (MIPS) or “embedded energy” taking account of all the energy going into a product from raw material through distribution to consumers to the final disposal of discarded units; reducing MIPS through durability and availability of replacement parts; new technology like electronic books and catalogues; steel versus concrete, favoring steel for applications like high-voltage transmission, pylons and bridges; water efficiency in a wide range of manufacturing processes; residential water efficiency; reducing waste in industry; reducing production of toxic chlorinated solvents through recovery and reuse; using less concrete for stabilizing walls; recycling wrapping plastic and reusing bottles, cans and large containers.
- Transportation-related efficiencies: videoconferences; electronic mail; reducing the transport intensity of consumer goods (“local blackcurrant juice versus overseas orange juice”, in the German context); public transport options like multiplying the capacity of existing railways and introducing resource-efficient new-technology fast trains; more fuel-efficient cars; lighter cars; car sharing and car renting; developing “urban villages” with co-located job opportunities, encouraging home-based businesses, and reducing local travel to walking and bicycling. (Expanding local rail networks in major cities come to mind too, in situations where people still have to commute across cities to work.)

More than a decade has passed since *Factor Four*, and the list would be different if compiled today. While undoubtedly missing some details, it does provide the most complete review we were able to find – with the qualification that these technologies are all material. As

Brian Arthur showed (Arthur 2009a), not only will design efficiency depend on the hierarchy of building blocks that are themselves technologies falling into place, but it also depends on the continued evolution of non-material technologies such as organizational design and knowledge systems.

LAND MANAGEMENT TECHNOLOGIES AND FOOD SECURITY

These technologies are concerned with the 45% of all carbon captured by photosynthetic activity on land, and other forms of sequestering carbon through natural processes. Most current technologies using natural processes to capture atmospheric carbon dioxide, or preventing greenhouse gases from escaping into the atmosphere, are land-based. It is recognized, however, that the oceans form the largest carbon sink accounting for the remaining 55% of photosynthetic activity (Nellemann et al. 2009). "Blue carbon", as the oceanic sink has been called, is considered in the next main section.

Before going more deeply into technologies that are directed towards reducing greenhouse gases, it is recognized that one of the world's top concerns over the coming forty years will be food security – how to meet demand from a world population one-third larger than today's, generating demand perhaps 70-80% higher. The new technologies have to coexist with this, and if possible help secure adequate food supplies across the planet. There will be formidable conflicting objectives as in the case of fighting climate change itself.

A *New Scientist* article (MacKenzie 2009) assesses four key ways to boost food production to "feed the 9 billion" – hold on to water, stop plowing, go back to basics, and boost yields. Focusing on developing countries, including Africa, holding on to water lost through evaporation or run-off, drip irrigation, no-till farming, better use of fertilizers and pesticides, and improving transport and storage systems which are currently preventing farmers from connecting effectively to markets, are energy efficient technologies. Some are "simply" about providing better roads for the produce to reach their market, reducing the great waste from poor distribution systems, and taking advantage of better communication facilities like the spread of cell phones for access to price information and other market data.

The fourth alternative, to boost yields through genetic engineering of wheat, corn, and rice, as recommended by organizations such as the International Food Policy Research Institute (IFPRI), would need to be balanced against the risk of perpetuating, or returning to, monoculture. The section on biotechnology below depicts an area of great technical potential with political and ethical implications that continue to be debated on issues like genetically modified organisms and "big" versus "small" agriculture. Biotechnology, however, is part of our common future, where food security is becoming a crucial issue as populations and economies continue to grow.

Chris Goodall's (2008) top ten technologies include, as previously noted, two that fit under the heading of land-based technologies: *biochar* – sequestering carbon as charcoal, and *soil and forests* – improving the planet's terrestrial carbon sinks. Australian earth scientist and paleontologist Tim Flannery also thinks solving the climate problem is to a large extent associated with managing Earth's land resources. Like other scientists, he regards high-tech geoengineering methods of drawing carbon dioxide out of the atmosphere as "hypothetical" at best. The strongest prospect of large-scale draw-down of atmospheric CO_2 lies in changes to our agricultural and forestry practices, including the biochar technology described below (Flannery 2009, pp 68-99). Peter Cosier (2008), as already documented, considers land management fundamental to managing the atmospheric CO_2 balance.

Allan Savory, long-term campaigner for sustainable agriculture, advocates a two-path strategy to combat climate change (Savory 2008, p 5). The technologies described below offer a parallel route to the *high technology path* "based on mainstream reductionist science [which] is urgent and vital to the development of alternative energy sources to reduce or halt future emissions." The *low technology path* is "based on the emerging relationship science or holistic world view [which] is vital for resolving the problem of grassland biomass burning, desertification and the safe storage of [the] legacy load of heat-trapping gases that already exist in the atmosphere."

Sustainable farming, in which the natural resources such as soil, nutrients, and water are retained, are defined by the following criteria in Australia (Lehane 2001, p 2):

- Long-term real farm income: real and average real net farm income, total factor productivity, farmers' terms of trade, debt servicing ratio.
- Natural resource conditions: nutrient balance (phosphorus, potassium), acidity and sodicity,[54] rangeland condition and trends, species diversity of agricultural plants, water used by vegetation.
- Off-site environmental impact: chemical residues in products, salinity in streams, dust storm index, impact of agriculture on native vegetation.
- Managerial skills: level of formal education, participation in training and organized land care activities, implementation of sustainable practices.
- Socioeconomic impacts: age structure of agricultural workforce, access to key services.

The emphasis would differ from country to country, region to region, and according to level of development, but in the process of building up criteria this would provide a reasonable checklist to start with.

Biochar

Biochar is a fine-grained charcoal-like material produced by heating biomass under air-deprived conditions (pyrolysis). Feedstock includes residues from forests or crop production, manure, and green waste. Pyrolysis at relatively low temperatures of 300-600^{O}C changes the chemical properties of biomass carbon into structures that are much more resistant to microbial degradation than the original organic matter. Thus, materials that would rapidly release CO_2 and other greenhouse gases as they decompose, are transformed into a material that degrades much more slowly, thereby creating a long-term carbon sink. Biochar has mean residence times of several hundred to several thousand years in soils (Lehmann 2009).

[54] Problems associated with acidity include an increase of toxic minerals, a decrease in the availability of some plant nutrients and decreased microbial activity. Soil sodicity causes the swelling and dispersion of clay particles in the soil, which can result in hard-setting and water-logging. The consequence of this can be significantly reduced crop and pasture yields (Hajkowicz and Young 2005).

Typically, about half the biomass undergoing pyrolysis is converted into biochar which can be returned to the soil. The rest becomes biofuels for transport and energy, or co-products (Figure 2). Nitrogen, ammonia and other nitrogen oxides, sulfur compounds, and carbon dioxide may be added to the biochar before returning it to the soil, to increase the carbon sink and nutrient contents (Krull 2009). Other useful additives include potassium and phosphorus (Goodall 2008, p 212).

Biochar differs depending on the feedstock; they may look alike but biochar from manure will have higher nutrient content than biochar made from woodchips, but the latter will be stable over a longer period of time. The heat treatment is also important. As an organic material, it is porous, but biochar produced at 700^{O}C has much higher adsorptive capacity (to bind particles to its surface), and is more porous than biochar produced at 400^{O}C. The higher heat makes it more capable of adsorbing toxic substances and rehabilitate contaminated environments (Krull 2009), and the porous structure helps retain nutrients and provides a structure that encourages the growth of valuable micro-fungi (Goodall 2008, p 212).

As a soil conditioner, biochar benefits soil quality in many ways including retention of nutrients, decreasing soil acidity, improving soil structure, and in the short term reducing the release of methane and nitrous oxide (Krull 2009).

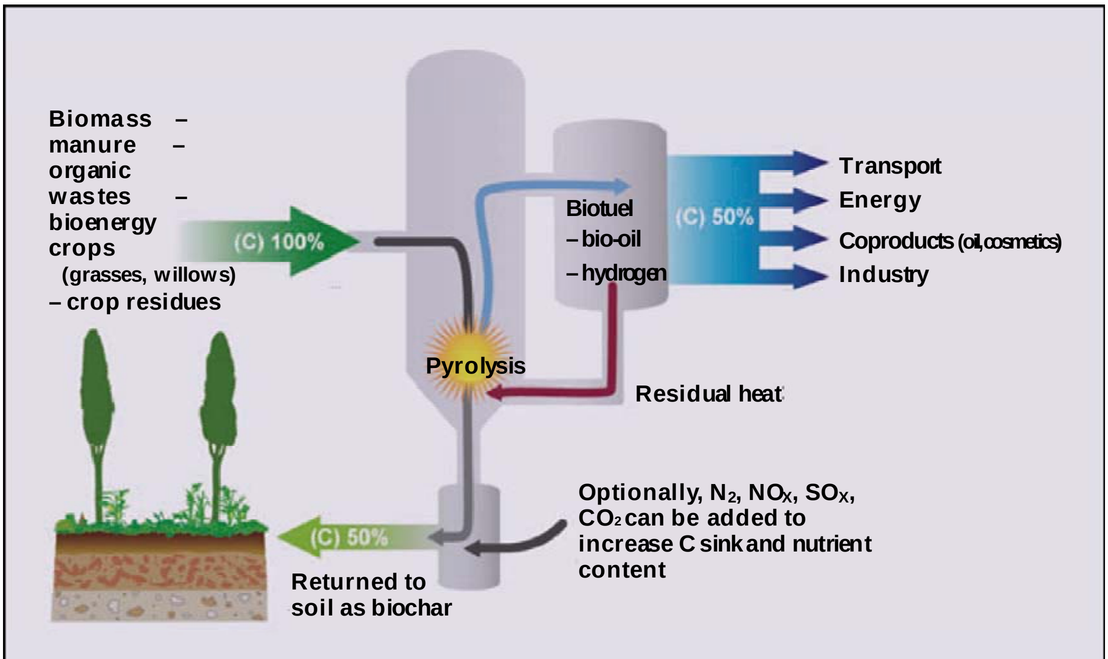

Figure 2: Concept of low-temperature pyrolysis bio-energy with biochar sequestration. Typically, about 50% of the pyrolyzed biomass is converted into biochar and can be returned to soil. Reproduced with the permission of the author and publishers from Lehmann (2007).

While charcoal burning is an ancient technology, and biochar is common in soil due to vegetation fires over thousands of years,[55] biochar is not yet being produced in great quantity. This may be associated with the cost of transporting the raw material to central

[55] The *terra preta* soils in the Amazon (Portuguese for ‘dark earth’) are an outstanding example, which literally gave rise to the idea of adding charcoal to the world’s soils to reduce carbon dioxide levels (Goodall 2008, p 211).

processing units, which suggests that the technology may be most economically applied to decentralized positions. Lehmann (2007, p 384) contests this, however: “Several carbon costs are associated with the land-based production of biomass, transport to the bio-energy plant, pyrolysis itself, and land application of biochar (the latter is much less costly for biochar than for biomass, due to the fact that the mass per unit carbon of biochar is about 60% that of biomass). Our preliminary calculations take all of these carbon costs into account and suggest that the energy balance for various feedstocks, such as corn or switchgrass, is very favorable.”

The potential of biochar to help mitigate climate change is theoretical at this point, because there are few full-scale biochar systems. The technical potential of biochar to contribute one gigaton of carbon removals annually by 2050 (incidentally the size of a Pacala/Sokolow “wedge”) will require carefully developed sustainability criteria, since the climate change mitigation value of biochar arises from several connected sources including energy and agriculture. “The potential for climate mitigation is highly variable from one biochar system to the next due to different feedstocks, scales, and applications, which requires careful evaluation. Biochar must be integrated into existing food production systems and not be an alternative to food production, make use of already developed best-management practices such as no-tillage or conservation agriculture, and, for efficiency, build on residue collection systems that are already in place.” (Lehmann 2009, pp 4-5)

One potentially attractive feature of biochar technology, as discussed above, is that it may work successfully at different scales despite transport costs allegedly disadvantaging large-scale production. At the lower end of the scale, biochar can be made in tiny kilns that double as efficient cooking stoves, using locally available materials for fuel and giving householders some charcoal to feed the soil. Some – maybe a large part – of the world’s deforestation is caused by families seeking wood for cooking (Goodall 2008, p 214).

At the higher end of the spectrum, a pilot plant has been built north of Sydney by the Australian subsidiary of US biomass technology company BEST Energies, Inc. (Madison, Wisconsin). In October 2008, this venture together with CSIRO Land and Water and the New South Wales Department of Primary Industries organized a meeting resulting in the formation of the Australian and New Zealand Biochar Researchers Network (ANZBRN) which aims to improve the coordination of biochar research and provide information about biochar and its benefits (Krull 2009). Evelyn Krull subsequently told the main Australian government broadcaster that three to five years’ more research would be needed before Australian farmers could start using it.[56]

Another firm, EPRIDA, Inc. is based in Athens, Georgia. Its pilot plant processes chipped green biomass into syngas for power production, bio-oil, and biochar which is subsequently being organically enriched from a parallel waste-processing processing process (Day 2009).

Johannes Lehmann of Cornell University, leading expert on biochar technology, summarizes the environmental benefits under the following headings (Lehmann 2007, pp 384-386):

- Combating climate change causing a net withdrawal of CO_2 from the atmosphere.

[56] http://www.abc.net.au/science/articles/2009/03/04/2507238.htm.

- Improving soil by returning half the CO_2 to the land, and improving soil fertility from the biochar itself.
- Reducing pollution of waterways by retaining nutrients such as nitrogen and phosphorus[57] in the soil, and lowering the amount of groundwater leached into groundwater or eroded into surface waters.
- Additional opportunities to reduce greenhouse gases by scrubbing air pollutants from flue gas (carbon dioxide, methane, nitrous oxide) .

Lehmann concludes (2007, p 386): "Bio-energy through pyrolysis in combination with biochar sequestration holds promise for obtaining energy and improving the environment in multiple ways. The technology has the potential to be carbon negative, which means that .. greenhouse gases would be removed from the atmosphere. This could be the beginning of a biochar revolution that is not only restricted to a bio-energy combination, but applicable to a range of different land-use systems. Compared to the limited amount of CO_2 that can be removed from the atmosphere by other land-based sequestration strategies, such as no tillage or afforestation, a biochar sink has the advantage of easy accountability and multiple other environmental benefits.

There are, however, possible pitfalls as well as gaps in our understanding of the science of biochar behavior in soil and how different pyrolysis conditions affect biochar ecology in the environment. Pyrolysis is currently being developed with the primary goal of maximizing the quantity and quality of the energy carrier, such as bio-oil or electricity. The optimization of biochar properties within a pyrolysis system has not been the focus of research to date, and biochar can have very different properties depending on the type of organic residue from which it is obtained and how it is produced. Certain production conditions and feedstock types can make the biochar completely ineffective in retaining nutrients and affecting atmospheric CO_2, or susceptible to microbial decay. Efforts similar to the development of fertilizers over the past century need to be undertaken to provide the underlying scientific information for biochar ecology that contributes to cleaner air and water while producing energy. The evidence overwhelmingly suggests that exploration and development of biochar bio-energy is highly promising."

In short, biochar technology is not yet ready to make a major contribution, but it shows promise, perhaps especially for its potential to increase agricultural productivity in the developing world.

Tropical forests

Tropical forests are particularly important because they grow steadily all year; they are also particularly efficient in keeping the planet cool through the transpiration of moisture and formation of clouds.

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[57] Another matter of potentially vital importance is that supplies of phosphate rock are dwindling; although experts disagree on how much is left and how quickly it will be exhausted, the deposits are a finite resource that could disappear within the century, maybe in decades. Cutting down on the use of phosphate-based fertilizers and improving their efficiency could be very important (Gilbert 2009).

Tropical rainforests – and mangrove areas – have the highest terrestrial biodiversity in the world. They are disappearing at an alarming rate, and the negative factor of deforestation is one of the greatest sustainability issues, because it has potentially explosive effects, as when a tipping point may be approaching which will cause galloping destruction of the remaining Amazonian rainforest, beyond the direct damage caused by the steady logging that has taken place over the years. There is scientific consensus that the gradual loss of this rainforest will eventually not just affect greenhouse gas levels but will also change global weather patterns, probably making large areas of the western hemisphere much drier than at present (Goodall 2008, p 248).

The rainforests in Indonesia and Malaysia are still being replaced by palm oil plantations, of which a large part of the output goes into biodiesel vehicles in Europe. Other rainforest areas range from India and Burma in the west, while Bangladesh has the largest area of mangroves – but Central Africa and Madagascar have the second-largest tropical rainforest areas in the world, next to South America. Central America and northern Australia are other significant tropical rainforest areas, all under threat including their rich biodiversity.

Reforestation and afforestation, respectively denoting replacement of lost forested areas, and new plantings, are important but the effects are long-term while the removal of tropical forests is a major short-term issue.

Deforestation in tropical areas may be partly due to large commercial farming interests wanting to expand production (like the Indonesian and Malaysian palm oil plantation operations). But Goodall (2008, p 249) points out that it also happens partly as a result of the decisions of millions of people trying to create new land on which to grow food. The effect of widespread woodland loss is to increase soil erosion and cut fertility.

The single most important change to cut these losses is probably to reduce the amount of wood cut down for cooking food. As in the discussion of biochar in developing countries, there are simple technologies that might help achieve this purpose. Fuel-efficient stoves are one possibility:

"About 2 billion people .. cook using wood or dung. We cannot really be sure of these figures, but some estimates suggest that each person needs about 800 kilograms of cooking fuel each year. Multiply the two numbers together and we get a global figure of about 1.6 gigatons of wood and dung used each year, of which about 800 million tons (50%) is carbon. UNEP says that forest loss produces about 1.1 gigatons of carbon a year, meaning that the cooking accounts for about three-quarters of the net loss of forest volume. Put another way, if we could cut the amount of wood fuel used in cooking stoves in half, this alone would reduce net man-made additions of carbon dioxide to the atmosphere by over 5%." (p 250)

These are remarkable numbers which might be accused of being glorified "back-of-the-envelope" estimates but do not seem to have been seriously criticized. Goodall goes on to suggest simple technologies such as fuel-efficient wood stoves, and solar cookers that focus the sun's rays on to a container of water (a minuscule version of the large-scale concentrated solar power technology described earlier).[58]

"Another promising technology is the use of biogas collectors. When human, animal and plant waste rots down, they give off methane, particularly if kept in enclosed containers or left in a rubbish dump or landfill site. In most parts of the world, this methane vents to the open air but if it is collected it can be burnt in simple stoves, replacing the need for woody fuels." (p 250)

The biogas technology also – and perhaps mainly, though again its potential in developing countries is an important consideration – lends itself to large-scale ventures, using farm waste including pig, cattle and chicken manure as feedstock in an anaerobic digestion process. This technology is widely used in Europe and is expected to gain further importance (Holm Nielsen and Oleskowicz-Popiel 2007). Piggeries are an important source but the plant needs to be large – based perhaps on 10,000 animals.

The original gas produced is about 50-75% methane and most of the remainder CO_2. To be fed into a gas grid it needs to be cooled, drained, and dried, cleaned for H_2S (hydrogen sulfide), and subjected to separation from the CO_2 for upgrading to natural gas quality.

Undoubtedly the list of possible technologies could be lengthened. Some of those described here may apply particularly to tropical areas, but the wood-burning issue goes beyond these into the temperate areas of China and Central Asia. This also takes us into the last headings in this background paper, dealing with improved agricultural management.

The annual meeting on climate change in Bali in December 2007 (UNFCCC COP-13) focused on emissions from deforestation and degradation of tropical forests in developing countries. It proposed a new mechanism, Reducing Emissions from Deforestation and Degradation (REDD), for inclusion in the successor to the Kyoto Agreement. REDD is described and discussed in Chapter 4 of Esteban et al. (2008).

Croplands

Sustainable agricultural practices vary from country to country. It is a simple concept that embraces a complex web of issues: the state of the soil, water availability, choice of crop, stocking rates, needs for pesticides, herbicides and fertilizer, climate variability, and

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[58] A pioneering solar energy project in Misa Rumi, a village high in the Andes in northern Argentina, was sponsored by the NGO Fundacion EcoAndina (http://www.ecoandina.org/en/4706/4733.html). It is situated in an area known as La Puna, which was never connected to the electricity grid. The Argentine government installed solar panels there in the 1990s to provide lighting and power pumps for drinking water. Solar energy has helped keeping villages and towns alive and dissuaded families from moving into larger regional cities.

The project uses a variety of technologies for solar-fired stoves, solar-heated showers, heating a commercial bakery, water pumps for local vegetable growing, and heating the village school through black-roof panels to take the edge off chilly mornings. The president of EcoAndina, Silvia Rojo, said that the technology is improving quality of life and reducing firewood consumption which has caused desertification in the region. She added that the project has sparked a lot of interest in other Latin American countries like Colombia, Peru and Bolivia, and worldwide, and that each of the solar technologies used in La Puna can be scaled up for larger communities (Stott 2009).

protection of biodiversity. Then there is a range of economic issues, such as markets and production costs. Developments in information technology will play a key role in managing the complexity. Any program to successfully develop a system of sustainable agriculture must have farmer involvement at all stages of its development, and must look at a farming system as a whole, not just at individual elements (Lehane 2001).

Lehane (2001)identifies four key issues for cropland management in Australia, a country used as an example only, given the differences that exist between nations:

- *Loss of biodiversity*: A productive soil is called a 'living' soil because of the enormous number and diversity of organisms that cycle nutrients through the soil, maintain its structure, and prevent outbreaks of pests and diseases. Above ground, many modern agricultural practices, including monocultures, poor crop rotation, pesticides and heavy machinery, reduce biodiversity to low levels and trigger even greater adverse responses, such as pesticide treadmills. Bio-fumigation presents one sustainable approach to suppressing soil-borne pests and diseases in crops, utilizing toxic compounds produced by brassicas (such as cabbages, turnips and mustard) to kill soil pathogens. Farmers can plant a brassica crop alternating with another crop to break the life cycle of soil pests and diseases, instead of using synthetic pesticides.
- *Dryland salinity* became more obvious when grasslands and savanna-type vegetation were replaced with crop and pasture plants. These annual crops take up less rainwater, so more water is added to the underlying water table. The water table then rises, bringing salt to the surface. What is needed for sustainability in these regions are farming systems that match the previous water use, thus halting the rise in the water table. One possible approach is ‘agro-forestry’ systems that combine tree growing with cropping and grazing. As with many environmental problems, there is not a single solution: options will vary enormously with local and weather conditions.
- *Acid soils*: The biggest losses in agricultural production come when acidity increases to the point where toxic elements in the soil, particularly aluminum, are dissolved. Adding lime is expensive on large areas. To promote sustainable management of affected areas, land-use approaches are being investigated that can slow or reverse the acid build-up, and working towards breeding crop and pasture varieties that grow well in acid soils.
- *Pests and weeds*: Integrated pest and weed management, based on a detailed understanding of the ecology and biology of the target organisms, is now seen as an important key to sustainable control. It can involve, for example, biological control, crop rotations, planting resistant or tolerant varieties, or using insect traps as well as sprays. Goals include keeping pesticide and herbicide use to a minimum and only using chemicals that are environmentally benign.

Holistic livestock management and other agricultural techniques

Allan Savory originated “holistic management”, applied to cattle raising and developed since the 1960s, in his native Zimbabwe. It considers families, their economies, and the environment as inseparable, enabling people to make decisions that simultaneously consider economic, social, and environmental realities, short- and long-term. He notes (Savory 2008) that rangelands are similar to croplands – if the soil is bare any time of the year, they will deteriorate and release previously stored carbon. At the same time the ability of such rangelands to store water is reduced. Because much of the soil in rangeland areas is bare, erosion from them is even higher than for croplands.

Savory developed his ideas while working as a game ranger on the African savanna, where the grasslands support herds of millions of ruminants including wildebeest and other antelopes. He noticed that the vast African herds constantly moved across the landscape, heavily grazing an area, trampling the remaining dry matter into the ground, liberally fertilizing the soil with urine and manure, and then rapidly moving on. An Australian soil carbon specialist, John Lovell, has noted that the bison had similar habits roaming the prairies of North America (Goodall 2008, p 241).

Lovell has also focused on methane, a natural product in ruminants from the microbial fermentation in their digestive system and present in their manure, and how to eliminate this greenhouse gas problem through holistic management techniques (Lovell and Ward 2008). Methane can be made carbon-neutral or better according to Mark Adams of the University of Sydney's Faculty of Agriculture, Food and Natural Resources. In the high-plains country of New South Wales and Victoria, soil with high organic matter has been shown to oxidize more methane than the livestock can produce (slightly offset by bacteria producing CO_2 during the oxidization process). Adams sees another challenge in minimizing emissions of greenhouse gases from conventional broad-acre livestock operations (Cawood 2009).

The holistic management procedure for livestock mimics the movement and grazing patterns of the wild herds of old (except that the result is achieved through fencing), minimizing overgrazing of plants while harnessing the beneficial soil-preparation effects of trampling hooves that knock down old vegetation, chip bare soil surfaces, and cover them with manure.[59] The resulting increase in vegetation gradually fills in bare spaces, keeping the soil covered year round, and once again storing both carbon and water, and helping to ensure food and water security.

According to Savory (2008), the dry rangelands alone are estimated to constitute over 4.9 billion hectares worldwide, and the medium to higher rainfall grasslands increase the area significantly. He claims an estimated 12 million hectares is currently managed holistically across Australia, Africa, Mexico, Canada and the United States, and that increasing soil organic matter by a modest 1% on 12 million hectares (120,000 km^2) would remove 3.6 gigatons of CO_2-equivalent greenhouse gases, as well as helping to reverse desertification of the world's rangelands.

Allan Savory's concept of holistic management of livestock is also known under names such as "cell-grazing" or "block-grazing". It has been applied to sheep, poultry, goats, and other animals as well as cattle. In Australia, to take an example, cell-grazing operations are found from Tasmania in the south, to extensive rangeland ventures in the north of the continent. Operations can range in size from, say, 60 head of cattle or less, to 3,000 or more.

[59] This argument in favor of hoofed livestock, within carefully managed enclosed systems, contrasts with the erosion and run-off problems met in conventional broad-acre operations.

It is also a growing activity in the highland country west of Sydney, Australia, where the author lives. The person who started the first cell grazing operation in the district in 1996 lists the following features of his relatively small operation – all features that apply to cell grazing whether at large or small scale: [60]

- There are nine enclosures, in which the cattle successively eats the grass down, until one to two days' feed remains, when they are moved to the next enclosure. The remaining grass is left as mulch for new growth, which is fertilized by the dung left behind.
- In this operation, the animals were weaned at eight months and marketed the month after, when reaching about 300 kg. No artificial feed or growth hormones were used. Various techniques ensured that cows and calves enjoyed stress-free conditions during the weaning process.
- Cell grazing is flexible, fitting a wide range of climatic and soil conditions. The cycle of returning to the first enclosure varies from as little as two months in areas with good rainfall. In large holdings, the livestock may be moved every 24 hours.
- To maintain sustainability, stock numbers are limited to match the weight of organisms fertilizing the underlying soil (most of the weight of grass is underground, where it benefits from the carbon-rich nutrition).
- Carbon is returned to the soil and not to the atmosphere, through rotting plant matter.
- It is easier to control internal parasites of cattle because the rotation from cell to cell in the grazing system breaks the natural cycle enabling the parasites to take hold. Poultry may be used initially to eat local parasites before sending in the cattle.
- Biodiversity is enriched through a multiplicity of different grasses that were previously not able to develop. Because different grasses contain different nutrients, the livestock diet is better balanced.
- The enriched biodiversity builds up year after year – when there has been a need to rip up existing cells in the system, they have taken 10 years to recover.
- Cell grazing is more economical on fertilizer, which is released slowly from the ground as required.
- Cell grazing encourages a smaller and more efficient composition of the agricultural workforce because it requires little or no machinery. If any is required, contractors are used. Small cell-grazing properties like the one described are virtually one-person operations.
- The need for haymaking to provide extra feed is eliminated in this type of self-sustaining system.

Other advantages could be enumerated. Qualitative research into cell-grazing in Queensland's rangelands finds that it is "an emerging ideology of pastoral ecology."

[60] John Martin, cell grazer in Oberon, Australia, personal communication. Now in his seventies, he recently sold the property described and is now running a smaller, eight-hectare four-cell operation breeding goats. This illustrates, once again, the flexibility of cell-grazing from large to small, and the suitability of different animals.

(Richards and Lawrence 2009) It has been described in terms of three foundations: family support, soil health, and animal health. Women have been observed to be relatively actively involved, whereas conventional grazing operations tend to be male-dominated .

Richards and Lawrence (2009) conclude (p 638): "Although cell grazing does not currently offer a significant challenge to conventional grazing and its associated environmental problems, it does offer the possibility that an alternative form of production is able to operate in a manner that is both economically viable and environmentally sustainable. Cell graziers have exhibited the ability to adapt to both market and climatic conditions by reconfiguring their own identities as producers, re-thinking cattle management techniques, embracing a new, more entrepreneurial business philosophy, and focusing upon the condition of the environment."

Other agricultural techniques are also important, such as zero-tillage to keep the carbon in the soil rather than exposing it through plowing, which degrades the complex molecules in the humus which preserve soil structure and provide nutrients for plants, into carbon dioxide, methane and other simple structures. Generally speaking, soils with high levels of complex molecules are best for the climate and agricultural productivity. In summary, the techniques mentioned in this section "are the simplest and most basic of the portfolio of solutions to climate change, but they may also end up by being the most effective." (Goodall 1998, pp 252-253).

Importantly, these solutions lend themselves to small-scale applications in the developing as well as the developed world – many small enterprises combined can have a huge direct effect as carbon sinks, and by "spreading the word".

Back in the 1990s, the authors of *Factor Four* (Weizsäcker et al. 1997) offered other suggestions, which are undoubtedly just a few of many techniques that might be, or are being, adopted in our still highly diverse world:

- Increasing the energy efficiency in animal husbandry, where the input-output energy ratio varies between very low for free-range chickens living mostly on what they can find on the farm, and very high for *industrialized* beef production using animal feed from overseas. "Reducing export subsidies [in Europe] would save taxpayers huge amounts of money and radically reduce energy demand from the farms. .. It seems more than plausible that the energy "demand" from agriculture and food processing can be reduced by a factor of four with essentially no sacrifice of wellbeing." (p 51)
- Growing crops where the climate is suitable, as opposed to wasting energy on growing tomatoes in huge greenhouses as in the Netherlands (p 53).[61]
- Improving water-use efficiency in commercial irrigation schemes. In dry Arizona, it has been possible through subsurface drip irrigation to achieve 95% efficiency. The water savings were accompanied by other benefits like reduced tillage, replacing plowing and other operations, and increasing crop yields by 15-50% (p 80).

[61] This may clash with another of the 50 examples in Weizsäcker et al. (1997), encapsulated as "whether to drink local berry juice rather than imported orange juice" in order to minimize transport costs and use of fossil fuel.

- Reinventing agriculture through perennial polyculture – possibly the most important idea on agricultural practices and one that sets out to reduce dependency on fossil fuels and the fertilizer industry, and biodiversity losses (pp 97-99). Wes Jackson[62] advocates in-depth exploration of how the never-plowed native prairie works as a basis for developing a diverse, perennial vegetative structure capable of producing desirable edible grains in abundance including perennializing the major grain crops. The key issues are: Can perennialism and increased seed yield go together at no trade-off cost to the plant? Can a polyculture of species out-yield a monoculture? Can perennial species planted in mixtures adequately manage all pests? Can a perennial polyculture sponsor all of its own nitrogen fertility needs? "The implications and potential impact of this work are global." (Jackson 2002)

  The work on perennial crops continues, especially in the United States. Stan Cox, Wes Jackson's colleague at the Land Institute in Salina, KS, in 2008 spoke on perennial cropping systems of the future at an agronomy conference in Adelaide, South Australia (Cox 2008). His message is summed up in this initial statement: "Agriculture's impact on the Earth has been amplified by industrial farming, but the fundamental problem has its origins 10,000 years ago, in the domestication of those annual crops that are still the staples of the global food supply. Annual crops, with ephemeral, often low-density root systems, have a lower capacity than do perennials to foster microbial ecosystems in the soil or micro-manage nutrients and water. .. Perennial grains, combined with established and novel sustainable-agriculture practices, could help end the 10,000-year-old conflict between food production and ecological health."

  Cox (2008) explains: "The replacement of native perennial root systems with the annual roots of crops has subtracted or reduced many of the elements (e.g. carbon pools, micro-organism populations, and root channels) that make soils healthy. Annual crops also require frequent soil disturbance, precisely timed inputs and management, and favorable weather in critical, often narrow, time windows. In one field experiment encompassing 100 years of data collection, perennial crops were more than 50 times more effective than annual crops in maintaining topsoil."

  He points out that there is a genetic cost involving in hybridizing perennials and annual crops, which have obviously acquired qualities that are essential for domestication. "Differences in chromosome number, lack of chromosome homology, and other factors can cause moderate to complete sterility and restrict genetic recombination in the progeny. The plant breeder working with such crosses must struggle with genomic disruptions while selecting to improve multiple traits simultaneously."

- Bio-intensive mini-farming. California-based Ecology Action since the 1970s has developed a system for highly productive and sustainable agriculture (Weizsäcker et al. 1997, pp 100-101). The system rests on four main principles: deep cultivation of the ground to provide for optimal root growth; production of compost crops to feed back to

[62] Wikipedia: 'Wes Jackson' (site accessed October 2009). Jackson is an American biologist and botanist with a Ph.D. in genetics who left academia in 1976 to found a non-profit institution, The Land Institute. He remains head of this institute, which describes its main goal as the development of Natural Systems Agriculture.

the soil; intensive spacing of plants in wide beds to create beneficial microclimates; and inter-planting of different plants to foil pests. The organization and its outreach has grown: the international network, as at 2009, covers most of Latin America and many other countries including Kenya, Zambia, Israel, Russia, Uzbekistan, Afghanistan, Nepal, India, New Zealand, and Micronesia. [63]

An Indian perspective on sustainable agriculture

Vandana Shiva is a former leading Indian physicist (quantum theory) who became involved in interdisciplinary scientific research in science, technology, and environmental policy. In 1982, she founded the Research Foundation for Science, Technology and Ecology, which led to the creation of Navdanya,[64] a biodiversity conservation program to support local farmers, rescue and conserve crops and plants that are being pushed to extinction and make them available through direct marketing. She is a prominent representative of new ways of dealing with sustainable agricultural production in developing countries.

She alleges that two myths keep the world poor (Shiva 2005). "First, the destruction of nature and of people's ability to look after themselves are blamed not on industrial growth and economic colonialism, but on poor people themselves. .. The second myth is an assumption that if you consume what you produce, you do not really produce, at least not economically speaking. If I grow my own food, and do not sell it, then it doesn't contribute to GDP, and therefore does not contribute towards "growth". .. Yet sustenance living, which the wealthy West perceives as poverty, does not necessarily mean a low quality of life."

While accusing rich countries of exploiting the developing world, for imposing western agricultural technologies including genetic engineering, and taking Jeffrey Sachs of the Millennium Project to task for "not understanding where poverty comes from", her Navdanya ("nine crops") program does represent an attempt to promote ecological agriculture based on biodiversity, for economic and food security. Navdanya pioneered seed saving, which began in response to the crisis of agricultural biodiversity, with the participation of the communities who have evolved and protected the plants and animals that form the basis of sustainable agriculture.

Navdanya is a gender-sensitive movement, led by women and putting women first. The gender program Diverse Women for Diversity seeks to strengthen women's grassroots movements and provide women with a common international platform to air their views.

Navdanya has worked with local communities and organizations serving more than two million farmers from all over India. It has established 34 seed banks in 13 states across the country "as it believes in operating through a network of community seed banks in different eco-zones of the country, and thus facilitating the rejuvenation of agricultural biodiversity, farmer's self-reliance in seed locally and nationally, and farmers' rights."

According to its website, Navdanya's efforts have resulted in the conservation of more than 2,000 rice varieties from all over India including indigenous rice varieties that have been

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[63] http://www.growbiointensive.org/.

[64] http://www.navdanya.org/.

adapted over centuries to meet different ecological demands, as well as conserving 31 varieties of wheat and hundreds of millets, pseudocereals[65], pulses, oilseeds, vegetables and multipurpose plant species including medicinal plants.

Again, the adoption of alternative technologies will differ between the four IPCC-based scenarios, which is the appropriate way of dealing with them.

THE OCEANIC CARBON SINK

Oceans represent the largest long-term sink for carbon and also store and redistribute CO_2. The ocean's important vegetated habitats are in coastal areas: mangroves, salt marshes, and seagrasses.[66] They cover less than 0.5% of the sea bed but rank among the most intense carbon sinks on the planet, accounting for more than 50%, possibly over 70%, of all carbon stored in ocean sediments. Microscopic plants known as phytoplankton (measuring from 200 µm down to 0.2 µm)[67] also consume CO_2 through photosynthesis and are an essential part of the carbon cycle. While tiny, phytoplankton contribute significantly to the carbon budget of the planet due to be vast areas that they inhabit (more than 70% of the planet's surface). The sinking of phytoplankton such as coccolithophores from the surface layers of the ocean represents an important pathway for the sequestration of carbon into the depths. This sequestered carbon may remain stored there for millennia, as distinct from rainforests where the period depends on the lifespan of the trees.

Even though the plant biomass in the oceans is only 0.05% of all land-based vegetation, it cycles almost the same amount of carbon. But while increasing efforts are being made to slow down land degradation (as described in the previous section), the role of marine ecosystems has to date been substantially ignored.

The United Nations Environment Program (UNEP) in cooperation with other organizations has published a report called *Blue Carbon* to rectify the neglect of the oceans as carbon sinks (Nellemann et al. 2009). The term "green carbon" has been used mainly to describe the role of forests as natural sinks – though it should be capable of extension to other land management technologies. The term "blue carbon" has now been coined specifically to distinguish the role of the oceans from the role of forests and other green terrestrial areas.

The warming of the oceans that has occurred to date (0.64^{o}C over 50 years) has already caused a dramatic trend in the melting of sea-ice in the Arctic. Changes in temperature lead to an increase in the ocean volume through thermal expansion, and result in changes to the structure and circulation of the ocean. Rising temperature also drives more intense tropical storms. These changes add to the seasonal water-column stratification and coastal "flushing" mechanisms, resulting in more polluted coastal waters, algal blooms, and preventing food particles to reach organisms living in the deep sea and on the sea floor.

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[65] Cereals are grasses. Pseudocereals such as buckwheat and amaranth are grains, not grasses.

[66] Mangroves and seagrasses are important in the Florida Keys. Salt marshes (tidal marshes) are common in Florida north of Cedar Bay and Daytona Beach but are replaced by mangroves further south (http://www.dep.state.fl.us/COASTAL/habitats/saltmarshes.htm).

[67] Micrometers or millionths of a meter.

The ocean also acts as a buffer for the Earth's climate by storing and exchanging CO_2 with the atmosphere, and diffusing it towards deeper layers. However, this continual intake of CO_2 and heat is changing the ocean in ways that have potentially dangerous consequences for marine ecology and biodiversity, because dissolved CO_2 in sea water lowers the pH level, which is already causing significant acidification and a loss of chemicals such as carbonate ions, leading to changes in the biogeochemical composition of ocean waters. There is substantial evidence that calcification by corals and other organisms such as coccolithophores (phytoplankton) is decreasing as a result of these changes (Raven et al. 2005, Kleypas and Langdon 2006, De'ath et al. 2009, Doney et al. 2009).

The changes to the physical and chemical conditions in the ocean are now directly affecting the distribution of plankton, fish and other marine fauna and in the migratory routes of many species. Last but not least in the context of this project, loss of coral reefs and associated biodiversity is listed specially as a major consequence of oceanic warming (Nellemann et al. 2009, pp 23-33).

From the technology angle, one reason the oceans have not been properly recognized in the context of climate change may be that they seem to lend themselves mainly to geoengineering proposals which are either in an early experimental stage or cause acidification (Nellemann et al. 2009, pp 42-43). Technology, however, is defined as means to fulfill a human purpose, which may not require a physical system but another "purposed system" (Arthur 2009a). In the context of this project such systems include marine sanctuary management, exemplified by the specialized organizations of the Florida Keys National Marine Park and Great Barrier Reef Marine Park Authority. Equally importantly, science itself, and the interface between science and technology, are purposed systems linking up with the marine sanctuary management organizations.

Vegetated coastal habitats – mangrove forests, salt marshes, and seagrass meadows – have been identified as by far the most important "blue carbon" sinks. They have much in common with rainforests, being biodiversity hotspots, providing essential ecosystem functions including their role as sinks, and experiencing rapid global decline. Vegetated coastal habitats rank amongst the most threatened ecosystems in the biosphere, with global loss rates 2 to 15 times faster than that of tropical forests, rapidly eroding the capacity of the biosphere to remove anthropogenic CO_2 emissions. Coastal eutrophication, reclamation, engineering and urbanization have led to the loss of a substantial fraction of the earth's blue carbon sinks since the 1940s (Nellemann et al. 2009, p. 45).

The main recommendations in *Blue Carbon* are, slightly abbreviated (from p 69):

1. Establish a global blue carbon fund for protection and management of coastal and marine ecosystems and ocean carbon sequestration, setting up mechanisms to allow the future use of carbon credits for marine and coastal ecosystems. Urgently upscale coastal zone planning and management especially near blue carbon sinks to increase the resilience of these natural systems and maintain food and livelihood security from the oceans.

2. Urgently protect at least 80% of remaining seagrass meadows, salt marshes and mangrove forests, through effective management and enforcement.

3. Initiate management practices that reduce and remove threats, and support the robust recovery potential inherent in blue carbon sink communities.
4. Maintain food and livelihood security from the oceans through comprehensive and integrated ecosystem approaches to increase the resilience of human and natural systems to change.
5. Implement mitigation strategies in the ocean-based sectors, including:

    a. Improve energy efficiency in the marine transport, fishing and aquaculture sectors, and marine-based tourism

    b. Encourage sustainable, environmentally sound ocean-based production, including algae and seaweed

    c. Curtail activities that negatively impact the ocean's ability to absorb carbon

    d. Ensure that investment for restoring and protecting the capacity of ocean's blue carbon sinks to bind carbon and provide food and incomes is prioritized in a manner that also promotes business, jobs and coastal development opportunities

    e. Manage the coastal ecosystems to encourage rapid growth and expansion.

This is much less physical technology than an integrated management system involving international organizations, national government authorities, and ecosystem managements. Scientists have an obviously integral role to play, whether employed in the organizations themselves, in universities, or elsewhere. However, this case serves as another reminder not to overlook non-physical approaches when exploring how to tackle climate change. The heart of the issue here is to save some very important ecosystems which are under severe threat. There are no obvious physical technologies ready to tackle this.

Finally, there is a need to expand the scientific knowledge in this area. While our understanding of the CO_2 storage potential of some ecosystems is fairly complete (for example open-ocean phytoplankton populations), we need to improve our understanding of many other ecosystems (such as coral reefs). It will also be important to gain a better understanding of the fluxes of other greenhouse gases such as methane. For example, the removal of mangroves from the coastline will not only lead to a reduced capacity to store carbon dioxide, but it will also lead to a potential increase in the flux of methane and other related greenhouse gases into the atmosphere from anoxic (oxygen-starved) mud and other consequences of mangrove removal.[68]

BIOTECHNOLOGY

Biotechnology is a technology domain based on biology, agriculture, food science, and medicine. It governs some technologies discussed in previous parts of this paper, especially biofuels. It is important, however, to acknowledge the profoundly important role of biotechnology as a discipline, not just how it has influenced particular technologies.

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[68] This section benefits from comments by Ove Hoegh-Guldberg on a previous draft.

While biotechnology is sometimes confused with genetic engineering, it encompasses a wider range and history of procedures for modifying living organisms according to human purposes, going back to domestication of animals, cultivation of plants and "improvements" to these through breeding programs that employ artificial selection and hybridization.

The United Nations Convention on Biological Diversity defines biotechnology as any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use. There are several branches of biotechnology, for example:

- Green biotechnology is biotechnology applied to agricultural processes. One hope is that green biotechnology might produce more environmentally friendly solutions than traditional industrial agriculture. An example of this is the engineering of a plant to provide its own pest control, replacing the need for external application of pesticides. Whether or not green biotechnology products and associated issues of food security are becoming environmentally friendly remains a topic of healthy debate, which appears to be gradually leading to greater public acceptance of mainstream green biotechnology.
- Red biotechnology is applied to medical processes. Some examples are the designing of organisms to produce antibiotics, and the engineering of genetic cures through genetic manipulation.
- Blue biotechnology has been used to describe the marine and aquatic applications of biotechnology, but its use is relatively rare. [69]
- White biotechnology is biotechnology applied to industrial processes. It has been defined as "a set of long-term strategies in which living cells and enzymes will be used to produce goods and services to mankind, with a smaller burden on the environment, using renewable resources, and promising better products at lower production costs in terms of energy, water and capital costs ." (Villadsen 2007, p 6957).

White biotechnology research is progressing "at a tremendous pace", which according to Villadsen (2007) "makes it almost certain that none of the second-generation industrial plants for making solvents, intermediates for polymer production, or transportation fuels will be based on the same fundamental science as the first generation production plants." Costs have come down by a factor of at least five over the past decade, and even more for cellulosic ethanol technology as noted in the description of individual technologies.

Villadsen concludes (2007, p 6967): "The expansion of industrial biotechnology to substitute many of the traditional petrochemical routes to commodity chemicals is expected to be very rapid. First of all the expansion is driven by the advances in molecular biology where increases in yield and productivity of the order of a factor ten within a few years of dedicated research are not impossible. The enormous experimental work required to find the right organism and the best operating conditions is greatly helped by the development of new analytical systems, by robotics and by miniaturization of the experimental equipment. But an equally important role is played by the efforts of many academic research groups to set up and solve complex models of the metabolism of the organisms, and by data

[69] Wikipedia on biotechnology, as at October 2009.

treatment methods that can handle both efficiently and correctly the enormous amount of data that result from the new experimental techniques.

It appears that the application of engineering principles and engineering intuition to develop new equipment for large-scale operation of bioprocesses is lacking behind. Consequently, many unit processes of considerable importance for the bio-industry are insufficiently researched, and are taught with lacking enthusiasm at many universities. To reap the full benefits of the scientific revolution in biology one must promote the parallel research and teaching in the engineering fields that relate to processes where enzymes and living cells are used as “chemical factories”.”

In conclusion, white biotechnology research is progressing fast with support from big business, and there may also be paths towards future “green revolutions” like the one that added a quantum leap to agricultural productivity in the 1950s and 1960s. “The projects within the Green Revolution spread technologies that had already existed, but had not been widely used outside industrialized nations – including pesticides, irrigation projects, synthetic nitrogen fertilizer and improved crop varieties developed through the conventional, science-based methods available at the time.”[70] The next time around it is reasonable to expect that breakthroughs in modern biotechnology may provide a range of safer environmental solutions. Given that genetic engineering is part and parcel of mainstream biotechnological research, community attitudes will remain a factor, likely to differ in the four scenarios.

NANOTECHNOLOGY

In 1959, Richard Feynman, who was to receive the Nobel Prize in Physics six years later for his contribution to quantum electromechanics, delivered a visionary lecture on micro-miniaturization, “the problem of manipulating and controlling things on a small scale” (Feynman 1959). It portrays nanotechnology, a then future technology not even named, in a nutshell.

Principally inspired by biology, he noted: “Biology is not simply writing information; it is doing something about it. A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things – all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want – that we can manufacture an object that maneuvers at that level!” (p 5)

“When we get to the very, very small world .. we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways.

Another thing we will notice is that .. all of our devices can be mass produced so that they are absolutely perfect copies of one another. We cannot build two large machines so that

[70] Wikipedia on the green revolution, as at October 2009.

the dimensions are exactly the same. But if your machine is only 100 atoms high, you only have to get it correct to one-half of one percent to make sure the other machine is exactly the same size – namely, 100 atoms high!

At the atomic level, we have new kinds of forces and new kinds of possibilities, new kinds of effects. The problems of manufacture and reproduction of materials will be quite different. I am, as I said, inspired by the biological phenomena in which chemical forces are used in repetitious fashion to produce all kinds of weird effects (one of which is the author).” (p 9)

Fifty years after Feynman’s visionary lecture, nanotechnology is flourishing in fields “as diverse as materials manufacturing, computer chips, medical diagnosis, biotechnology, energy and national security” (Esteban et al. 2008, p 10). University institutes devoted to nanotechnology research are found everywhere. Defining nanotechnology as “science and engineering resulting from the manipulation of matter’s most basic building blocks: atoms and molecules”, Esteban and his co-authors have explored the importance of the technology relative to climate change for the United Nations University Institute of Advanced Studies (UNU-IAS, based in Yokohama, Japan).

Nanotechnology is a “platform technology” (and a “domain” in Brian Arthur’s (2009a) terminology) whose role if found technically and economically viable is to play an enabling role in other domains such as (Esteban et al. 2008, p 11):

- The hydrogen economy: hydrogen as an energy source using electrolysis and photolysis, automotive fuel cells, hydrogen storage in light-metal hydrides and carbon nanotubes, and molecular sponges which mop up CO_2. It could have a potential role in many applications of nano-engineering.
- Fuel efficiency: Fuel additives to catalyze fuel efficiency and reduce emissions such as cerium oxide powders and cerium salts which absorbs some CO_2 from the atmosphere, Improved lubricant additives to minimize corrosion and energy performance, nano-detergents to improve engine performance, nano-structured coatings for turbines, and catalytic converters.
- Photovoltaics and other solar energy: nano-particle silicon systems; mimicking photosynthesis; nano-particle encapsulation in polymers; use of non-silicon materials such as calcopyrites to develop thin film technology; molecular organic solar cells; organic polymer photovoltaic systems; development of single-walled nanotubes in conducting polymer cells; nitride solar cells; flexible film technology; and development of novel nano-structured materials.
- Energy storage: For electric and hybrid cars, supercapacitors, electric trains, trams and trolley buses; batteries for portable consumer information and communication technology, such as laptops and mobile phones.
- Insulation: Insulation for buildings to save on heating and cooling; foam insulation including aerogels in the nanometer range characterized by their thermal properties and extremely low density; glass fibers, glass, and vacuum insulating panels.

Nano-catalyst materials can also give better selectivity for chemical reactions and thereby save raw materials and investment costs.

While there are potentially many benefits offered by nanotechnology for responding to climate change, there are also potential risks that nanotechnologies present to humans. As nanotechnologies are an emergent field of science and technology, the risks to humans, animal health and the broader environment cannot yet be determined. “The most significant issues raised so far relate to the toxicity of manufactured nano-particles and their ability to enter the human body and reach vital organs via the blood. However, there are still significant gaps in knowledge about how nano-particles act, their toxicity and how to measure and monitor nano-particle exposure.” (Esteban et al. 2008, p 16)

“Given the sophisticated and expensive nature of nanotechnology R&D, there are also ethical issues raised concerning the ability of less developed countries to benefit from and sustainably manage such advances in technology. What is unclear is whether less developed countries will be able to readily access this new technology, and perhaps more importantly, whether they have the capacity to properly assess and manage potential risks.” (p 17)

In conclusion, nanotechnology is or will be making useful contributions to particular applications like those mentioned in the dot points above. It is less likely to help solve any large-scale structural change toward renewable energy sources, and there may be problems diffusing nanotechnology to the smaller less-developed countries and regions.

TECHNOLOGY DIFFUSION

OVERVIEW

Brian Arthur’s focus is on the nature of technology, the title of his book (Arthur 2009a). In our context, apart from considering possible technologies that may “save the world” by reducing greenhouse gas emissions, there is another critical issue – how diffusion of technologies may also help “save the world”. This means focusing on the developing world, with special reference to the fifty least developed countries, of which two-thirds are in Sub-Saharan Africa. “The two greatest problems of our times – overcoming poverty in the developing world and combating climate change – are inextricably linked” (Stern 2009, p 8).

Technology typically spreads across the world through trade, foreign direct investment, and communications between organizations, academics, and expatriates across the borders. Major innovations and inventions, which are the cutting edge of technological change, tend to take place in high-income economies. Whether these patterns are changing is a main concern in this section.

The World Bank publishes an annual report on *Global Economic Prospects*, with a special theme each year, backed by empirical research. In 2008 the theme was technology diffusion to the developing world (Burns et al. 2008). The report found that up-front innovation and invention is largely carried out by high-income countries, dominated by the OECD. Even the 46 countries classified as “upper-middle income” accounted for very little – countries including Argentina, Brazil, Chile, Hungary, Malaysia, Mexico, Poland, Russia, South Africa, and Turkey.

To become involved in research, people born in developing countries move to high-income countries; the report notes that 2.5 million of the 21.6 million scientists and engineers working in the United States were born in developing countries. This itself must provide a source of technological inspiration across the borders, and therefore a likely source of innovative advance in developing countries.

China and India are included among the developing countries which according to the World Bank report generate little original innovation (a view challenged below), but the level of aggregation prevents any analysis of differences within countries, and the World Bank report acknowledges that there are at least pockets of innovative technology: "Despite a level of technological achievement in major cities that can rival that in high-income countries, low levels of technological advancement in rural areas mean that, viewed as a whole, countries such as China and India are not particularly technologically advanced. Moreover, because technology spreads slowly across firms, there are wide differences in the technological sophistication of production, even within the same sector in the same country. " (p 52).

This report finds that more new technology is beginning to develop independently in these countries. In upper-middle income countries the gap is already narrowing, especially in Hungary, Poland, and Chile during the past 10 years (Burns et al. 2008, p 52). But before going further, we need to present the World Bank's model.

THE WORLD BANK APPROACH

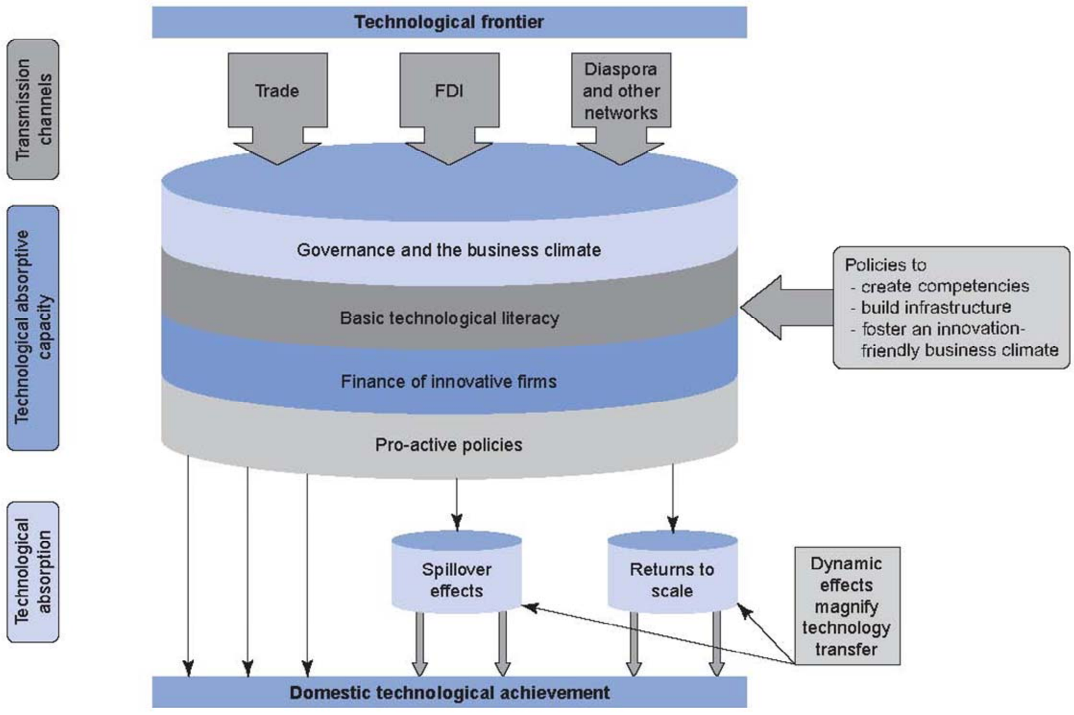
"In exploring technological achievement and diffusion, the World Bank report adopts a broad definition of technology and technological progress, one that encompasses the techniques (including the way the production process is organized) by which goods and services are produced, marketed, and made available to the public. Understood in this way, technological progress at the national level can occur through scientific innovation and invention; through the adoption and adaptation of preexisting, but new-to-the-market, technologies; and through the spread of technologies across firms, individuals, and the public sector within the country." (Burns et al. 2008, p 2)

Figure 3 is reproduced with World Bank permission, with explanations from the source added below the diagram. Generally: "A central finding of the report is that most developing countries lack the ability to generate innovations at the technological frontier." (p 3) "The bulk of technological progress in developing countries has been achieved through the absorption and adaptation of pre-existing and new-to-the-market or new-to-the-firm technologies, rather than the invention of entirely new technologies." (p 7)

The main empirical results of the World Bank research are:

1. The technological frontier has advanced as high-income countries continue to outperform developing countries at a rapid pace with basic innovations, so the innovative technology gap remains large between high- and low-income countries.
2. Developing countries have progressed markedly in the past 15 years. As a result, technological achievement (as distinct from innovative or inventive technology) has advanced more quickly than in high-income countries.
3. The convergence of technical achievement reflects substantial improvements in the openness of developing countries to foreign trade, foreign direct investment, and international migration. This has dramatically increased both the exposure of developing

countries to new technologies and their opportunity to use foreign markets and exploit increasing returns to scale.



Source: World Bank.

Figure 3: Stylized description of how a developing country absorbs technology. An economy is exposed to higher-tech business processes, products, and services through foreign trade, foreign direct investment, and contacts with its diaspora and other networks such as academia and international organizations (the large arrows at the top of the figure). The larger these flows, the greater the exposure of the economy to the global technological frontier.

However, exposure to new ideas and techniques is not sufficient to ensure that the technology diffuses through the economy. Successful absorption of foreign technology depends on the technological absorptive capacity of the economy (represented by the multiple-ringed drum). This capacity depends on the overall macroeconomic and governance environment, which influences the willingness of entrepreneurs to take risks on new and new-to-the-market technologies; and the level of basic technological literacy and advanced skills in the population, which determines a country's capacity to undertake the research necessary to understand, implement, and adapt them. Because firms are the basic mechanism by which technology spreads within an economy's private sector, the availability of finance for innovative firms through the banking system, remittances, or government support schemes is also important for the speed of the absorption process.

Finally, pro-active government policies are crucial. Governments are often the primary channel through which technologies are delivered. Moreover, government policy is largely responsible for creating a business environment that facilitates easy entry and exit and that is not hostile to the profits to be made from exploiting new technologies.

[From Burns et al. (2008), pp 8-9. Reprinted with permission from the World Bank as copyright holder.]

4. Absorptive capacity has progressed through improved literacy and education, and better macroeconomic stability. But progress in improving the business climate and governance indicators has been much more mixed. This has put a restraint on the technological absorptive capacity of developing countries, at least for now.

The research covered two periods, the early 1990s (1990-93) and the early 2000s (2000-03). The comparison reveals some significant developments, including strong growth from a very low base for developing countries (Figure 4). The top panel shows the *level* of technological achievement split between innovation/invention and penetration of older and recent technologies. The older technologies are fixed-line telephony, electric power, transportation, and health care services. The recent technologies are the Internet, personal computers, cell phones, percentage of digital mainline, and high-tech exports.

Penetration →	Scientific innovation and invention	Older technologies	Recent technologies
A: Technological achievement			
High-income countries	100.0	100.0	100.0
Upper-middle income countries	3.3	58.4	49.6
Lower-middle income countries	0.6	41.6	31.8
Low-income countries	0.1	23.7	22.7
B: Increase in technological achievement			
High-income countries	100.0	100.0	100.0
Upper-middle income countries	191.6	220.8	162.3
Lower-middle income countries	157.1	251.8	145.8
Low-income countries	63.7	480.4	411.3

Figure 4: The top panel shows the technological achievement in developing countries relative to that in high-income countries, as percent of the level in high-income countries. Innovative and inventive activity is very low in the rest of the world, and introduction of technologies has been largely through older and recent technologies developed elsewhere. The bottom panel shows the ***increase*** *in technological achievement between 1990-93 and 2000-03, using the change in high-income countries as an index. Though still low, the rate of growth in middle-income countries exceeded the growth in high-income countries, but this was not the case for low-income countries. These countries, however, showed much higher growth than any other country group in importing both older and recent technologies.*

Source: World Bank, reproduced from Tables 2.11 and 2.12 in Burns et al. (2008, p.81).

The lower panel shows the *change* between the early 1990s and the early 2000s, with two quite remarkable findings:

- The introduction of innovation and invention in upper-middle income countries almost doubled relative to the high-income countries, and was almost 60% up in the lower-middle income countries, albeit from very low bases. Only the low-income countries did not perform as well as the developed countries on this criterion.

- The low-income countries, however, produced the second remarkable finding. For both older and more recent technologies, they showed by far the greatest growth (between four- and five-fold) relative to the high-income countries, indicating considerable catch-up. Middle-income countries also showed high relative growth of some 250% for older technologies and 150% for recent technologies. The relative growth was generally higher for older than for recent technologies, presumably because growth rates were high for the latter in the high-income countries too.

The World Bank report (Burns et al. 2008) contains an analysis of a comprehensive data set called CHAT (Cross-country Historical Adoption of Technology) compiled by the National Bureau of Economic Research, which traces the extent of diffusion of some 100 technologies in 157 countries between 1750 and 2003 (Comin and Hobijn 2009). The report notes two important points emerging from this analysis:

- First, technology diffusion across the globe has accelerated over time. For transportation, communications, and manufacturing technologies discovered between 1750 and 1900, it took an average of 107 years before they reached 80% of countries covered by the analysis. The average declined to 61 years for technologies discovered between 1900 and 1950, 24 years for those discovered between 1950 and 1975, and 16 years for those discovered between 1975 and 2000. There are similar patterns within each of the three technology groups, and for medical technology which covered OECD countries only. [71]

- Secondly, technological diffusion appears to accelerate above a certain threshold, defined as a percentage of the average level of the 10 countries where the technology is employed most intensively.

  For the world as a whole, the amount of time required to go from the 5% level to the 25% level is much smaller than the time required to reach the 5% level. Between 1900 and 1950, it took an average of 52 years to reach the 5% threshold, but only an additional 13 years to reach 25%. Moreover, the pace of acceleration has increased over time. For technologies introduced since 1975, dominated by electronics and information technology, it took an average of 16 years from its invention for a technology to reach the 5% threshold in a given country, but only another three years to reach the 25% threshold.

INDICATIONS OF EXPANDING DIFFUSION RATES

A special report in *The Economist* on innovation in "emerging markets" (what used to be called "the developing world" or even "the third world") contains the clearest indication yet that innovative effort is spreading rapidly and that the "emerging world" now rivals the rich countries for business innovation (Wooldridge 2010). Before that article was published, the current section of this background paper (unchanged except for this and the next paragraph)

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[71] Cataract surgery holds the record among the technologies listed in the World Bank report, taking 251 years to reach 80% of countries. The technique goes back to antiquity but Jacques Daviel performed the first successful extraction in Europe in 1748 (Wikipedia). This suggests that 80% country penetration was not reached until the end of the 20th century.

had already found plenty of evidence that the World Bank report was rapidly becoming outdated.

There are now around 25,000 multinationals based in the emerging world according to the United Nations. “The best of these .. are as good as anybody in the world. The number of companies from Brazil, India, China or Russia on the *Financial Times* 500 list more than quadrupled in 2006-08, from 15 to 62. Brazilian top 20 multinationals more than doubled their foreign assets in a single year, 2006.” (Wooldridge 2001, p 3 – the 16-page special report is recommended reading in full).

In contrast, the World Bank report suggests that within its long-term perspective (to 2030), inventive ability will remain largely with the high-income countries. This is highly debatable. Anyhow, the time perspective adopted in the World Bank report is much shorter than for the four IPCC-based scenarios, and our assumptions must vary with each storyline.

The indicators of technological innovation and invention are the number of scientific journal articles and United States and European patents granted per million population. The report itself comments on some shortcomings of these,[72] and they also appear to be at loggerheads with Brian Arthur’s organic and evolutionary model (Arthur 2009a), according to which innovations give rise to other building blocks of innovations in an continuing process .

The complexity should be duly acknowledged. Bhidé (2009) in an exposé on “the three levels of technology” comes to similar results as Arthur (2009a), who was described in Hoegh-Guldberg (2010c) as a leading exponent of complexity theory. Using computers as an example, there are high-level building blocks or raw materials (microprocessors and the silicon used to make them), mid-level intermediate goods (motherboards and their components), and ground-level final products (the computers themselves). Furthermore, the invention would not see the light of day without know-how ranging from high-level understanding of solid-state physics, through knowing at mid-level about circuit designs and chip layouts, to maximizing yields and quality in semiprocessor fabrication plants at ground level.

Not only does the new invention depend on the other levels of technology developing the appropriate support technologies. It would not sell very effectively without adjustments to organizational and marketing technologies (“purposed systems” in Arthur’s terminology). Finally, globalization has caused innovation and technological development to become much less dependent of a particular nation, which is important for our understanding of diffusion:

“In a world where breakthroughs travel easily, their national origins are fundamentally unimportant. .. An Englishman invented the World Wide Web’s protocols in a Swiss lab. A Swede and a Dane started Skype, the leading provider of peer-to-peer Internet telephony, in Estonia. .. What is true for breakthroughs from Switzerland, Sweden, Denmark, and Estonia is true as well for those from China, India, and other emerging economies. We should expect

[72] “Finally, most indicators tend to be biased toward goods (as opposed to services), and among these, toward electronic and other high-tech goods. Most measures also focus on product technology (goods and services that themselves are highly technical) rather than final (or intermediate) goods and services that may be technologically unremarkable, but which are the result of a technologically sophisticated production process, for example, maize that is produced using sophisticated crop rotation methods, enhanced irrigation and fertilization strategies based on satellite imaging, and bioengineered seeds.” (Burns et al. 2008, p 60)

– and desire – that as prosperity spreads, more places will contribute to humanity's stock of scientific and technological knowledge. The nations of the earth are not locked into a winner take-all race for leadership in these fields: the enhancement of research capabilities in China and India, and thus their share of cutting-edge work, will improve living standards in the United States, which, if anything, should encourage these developments rather than waste valuable resources fighting them." (Bhidé 2009, p 4)

Anecdotal evidence gathered through the review of technologies in the previous sections suggests that the western dominance may be in for some competition. The development of the bioethanol industry based on sugar cane was said to be based to a large extent on Brazil's own technology research (Goldemberg 2007); even if this research was arguably derived from basic research undertaken elsewhere, it may at the very least contain the germs of future basic research in Brazil.

Writing on "white" (industrial) biotechnology, Villadsen (2007, p 6958) notes: "China will .. supplant much of its fossil fuel import with bio-fuels, but the momentum of Chinese investments in research will soon make China one of the foremost exponents of a bio-based economy. India, China, Japan, Korea, and even the smaller economies of South East Asia seem to be bristling with ideas for bio-based routes to fine chemicals production."

John Villadsen is a leading academic biotechnologist with a lifetime of experience with industries in Latin America, Asia, and elsewhere. Two years after the paper quoted above, he summed the current situation and prospects up in his own professional field, referring to those countries where he has most recent experience: [73]

- In Brazil, the burgeoning bioethanol industry will accept that both the primary product, sugar, and the 80% of the plant that is not sugar must be utilized for ethanol production. Then Brazil will develop a large chemical industry where most of the valuable clean sugar is used to produce chemicals, while a large export of ethanol is maintained based on the rest of the biomass. This enormous change will continue to require innovations developed in Brazil.
- India is "a kettle boiling over with new ideas." Its 15 so-called IITs (Indian Institutes of Technology) are "brilliant". They were all founded (or upgraded to IITs) since 1950 and six new IITs were opened in 2008 alone. Three more are being planned.[74]
- Thailand is "massively into biotechnology, including academic research of a high caliber." The National Center for Genetic Engineering and Biotechnology (BIOTEC) is under the umbrella of the Thai Government's National Science and Technology Development Agency (NSTDA). A 80-acre Thailand Science Park outside Bangkok provides main laboratories, incubator units, pilot plants, greenhouses and accommodation as well as financial, management and legal support for NSTDA, BIOTEC and private customers. Its main objective is to develop the capability for conducting research, development and engineering in the area of genetic engineering and biotechnology.[75]

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[73] From Nielsen, Villadsen and Lidén (2010, Chapter 2), supplemented by information on IITs and Thai activities.

[74] Wikipedia on Indian Institutes of Technology.

[75] http://www.business-in-asia.com/thailand_biotechnology.html.

- Leading Danish multinational companies Novo Nordisk (biopharmaceuticals, with a leading position in diabetes care) and Novozymes (which focuses on second-generation bioethanol from waste and agricultural residue with an ambition to "drive the world towards sustainability") place much of their research and development work in India and China where they collaborate with highly skilled scientists and technologists. China is becoming a strategically important market for both insulin and industrial enzymes.
- These companies, and others, support the new developments, believing that much new research into biotechnology will happen in countries not expected, some decades ago, to ever reach the innovative activity in North America and Western Europe.

There are further indications that the findings of the World Bank report undervalue a rapidly changing situation, especially in China. The Chinese Ministry of Science and Technology describes a rapidly expanding science and technology sector increasingly innovative in its own right. An issue of the Ministry's *Newsletter* celebrating the 60 years since the formation of the People's Republic shows that the number of Chinese journal papers in 2008 achieved third place in the Thomson Reuter's Science Citation Index, and that Chinese innovation grants (presumably meaning patents) came fourth. The number of journal articles and international patents are the prime components of the World Bank's own indicators of innovation.[76]

When the country was opened up, the development of Chinese science and technology was initially based on imported advanced technologies, but it now enjoys an innovative capability in emerging technologies, including new energy. The fast development of high-tech businesses backed by national science parks "has made China's high-tech industry a promising industry with huge perspectives." The sheer size of the industry is impressive: 42 million science and technology personnel including "a high caliber R&D contingent of 1.9 million person/year."

Other issues of the Chinese *Newsletter* describe the high-level cooperation between the United States and China in 2009, starting with Energy Secretary Steven Chu's visit in July which resulted in the establishment of the China-US Clean Energy Research Center on July 15. There are numerous other mentions of international cooperation, including at least two in nanotechnology (Denmark, Australia), cooperation on information technology with Europe, and a general effort to diffuse energy efficiencies and environmental protection technologies (with Japan and Korea). In July China launched its Golden Sun Pilot Project to speed up 500+ megawatt photovoltaic solar projects. Also in July, Fengfa Technology in Shenzhen put the world's first semi-direct drive wind turbine at the megawatt level on public display. This involved new technologies resulting in 24 patents.

The World Bank report itself contains several more examples of innovative activities in the developing world:

- Examples from Chile, Kenya, and Indonesia show that technological innovation may spur further innovation in upstream and downstream activities (Burns et al. 2008, p 56).

[76] Newsletter No. 562 (October 30, 2009). (http://www.most.gov.cn/eng/newsletters/2009/index.htm).

- "Increasingly, venture capitalists and "business angels" are playing a role in financing new technologically sophisticated firms in developing economies. .. Even though empirical evidence is still scarce, this activity appears to be translating into increased innovation. .. Western-based venture capitalists are increasingly becoming involved in markets in Asia (China and India), Eastern Europe (notably the Czech Republic, Hungary, and Russia), and South Africa." (p 140)
- Government-sponsored innovation of Brazilian biofuels is behind the flex-fuel car engine, which can run on any combination of ethanol and gasoline. It was introduced in 2002 and, along with the surge in crude oil prices, has led to a revitalization of ethanol in Brazil (p 144).
- Petrobras in Brazil is now recognized as a world leader in all phases of deepwater petroleum technology (p 62).
- The Korean government program of technological development and innovation financing includes research centers located within corporations to supply industry with high-tech research capability. Industry dictates the focus and area of research. (p 145)
- The technological diversity across Chinese or Indian provinces was not picked up in the aggregate measures developed by the World Bank. Large technologically sophisticated cities, such as Mumbai or Delhi, are being well ahead of areas that lag behind in economic development (p 60). OECD has estimated that 70% of high-tech trade (both imports and exports) in China originates in four regions (Guangdong, Jiangsu, Shanghai, and Beijing) and is highly correlated with R&D intensity and foreign firms (p 112).[77]

The process of technology diffusion has entered a significant new stage, which is important in any assessment of the future. The major technologies originally adopted throughout the world included fixed-line telephony, electric power, transportation, rail and road infrastructures, educational institutions, sanitation networks and health care services – all expensive to create and maintain, and relying on large numbers of individuals with mainly modest technical skills. These older technologies depend on what governments have delivered in the past – mainly education and basic infrastructure (pp 4-5).

Older technologies, however, remain vitally important for food security: better roads for transporting produce, better storage facilities to reduce waste. This point was made prominently at the start of the section on land management technologies. One thing is to manage the land, another to distribute and market the produce effectively and profitably.

[77] The OECD publication is Liu and Remøe (2007). In general, the regions on the east coast are more innovative than the provinces in the central and western parts of China. Regional levels of innovation are highly correlated with their GDP per capita and their contribution to high-technology exports, but less with their shares in national R&D expenditures (p 26). The benefits of economic development are unevenly distributed across regions and between urban and rural populations. Large migration flows to urban areas exert pressure on the social fabric and the environment (p 59). The rapid development of small technology-based firms is an encouraging trend, which is partly a pay-off from the huge investment China has made in the development of science parks and incubators. Many of these small firms remain dependent upon public support to tenants of science and technology parks. But there is a recent emergence of more purely market-based innovative networks of small firms in some regions, notably Zhejiang, Jiangsu and Guangdong (pp 31-32).

The penetration of newer technologies such as mobile phones, computers, and the Internet has been considerably faster. The infrastructure is cheaper and requires fewer (though more skilled) workers to maintain. Moreover, costs are being dramatically reduced, in a continuing process. In many countries, the private sector can now offer these services in a competitive environment in contrast to the state-owned, monopolistic environments of the past. Furthermore, demand for these products has been boosted by low end-user costs as a result of competitive pricing strategies and because some of these newer technologies lend themselves more easily to sharing than do some older technologies (pp 5-6).

IMPLICATIONS FOR THE WORLD'S LEAST DEVELOPED SOCIETIES

Village-based technological development may have the best chances of improving the conditions of the world's poorest, many living in traditional village societies. Two developments in particular look encouraging.

First, the Grameen Bank originated in 1976 when Bangladeshi economist Muhammad Yunus launched a research project to extend banking facilities to the poor in Bangladesh, providing micro-enterprise loans to villagers, especially women. The aim was to enable households to reverse the vicious circle of low income, low savings, low investment, also known as the poverty trap.

In September 2009 the Grameen Bank had 7.95 million borrowers, 97% of whom were women. The bank has grown to 2,559 branches, works in most of the country's villages, and the loan recovery rate is 98%.[78]

Grameen Foundation, a nonprofit organization headquartered in Washington, DC with an office in Seattle, Washington, was founded in 1997 by friends of Grameen Bank to help microfinance practitioners by spreading Muhammad Yunus's philosophy worldwide. The Foundation has no financial or institutional links with the Grameen Bank. It is active in Sub-Saharan Africa, Asia, Middle East/North Africa, and the Americas, and concentrates on helping poor people, mostly women and children, improve their lives.[79]

Secondly, cell phones have evolved in a few short years to become tools of economic empowerment for the world's poorest people, compensating for inadequate infrastructure, allowing a freer flow of information, making markets more efficient, and unleashing entrepreneurship. Mobile density (cell phones per 100 persons) reached 100% in South Africa in 2009, and 98% in Ghana, and is reported to have reached 40% for total Africa.[80] The impact on communications and village economies generally is dramatic, covering everything from agricultural information services to matching sellers and buyers of agricultural produce and commodities.

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[78] http://www.grameen-info.org/index.php?option=com_content&task=view&id=26&Itemid=0. Muhammad Yunus and Grameen Bank jointly received the Nobel Peace Prize in 2006, and Dr Yunus was one of 16 recipients of President Obama's 2009 Medal of Freedom.

[79] http://www.grameenfoundation.org/who-we-are.

[80] This does not mean that 40% of every person has a cell phone, as one person can own more than one handset or SIM-card..

This development is paralleled by a strong increase in mobile broadband subscribers, a technology that is expected to surpass the number of fixed broadband subscribers and to extend the use of the Internet to the whole of humankind. Hamadoun Touré, secretary-general of the International Telecommunication Union, says that the next task is to ensure that everyone who wants to can use mobile technology to access the Internet. Like many in the industry, he predicts that this will be done using low-cost laptops ("netbooks") connecting to the Internet via mobile networks. After further cost reductions to below $100, this could evolve into a village-netbook model, the Internet equivalent of the village-phone model. It would provide a stepping stone to wider Internet access in the poorest areas, just as village phones did for telephony (Standish 2009).

These developments are among the most dramatic in the fight to reduce the poverty of the least developed countries. There seems to be a whole cluster of associated special technologies which might in time develop into a new technological domain in Brian Arthur's terms (Arthur 2009a).

A special investigation of policy options for sustainable energy development for Africa (Chapter 1 of Takada et al. 2007) presents a large canvas, leaving no doubt that the task is difficult (p 4), despite the new developments just described:

"Over the last four decades, the gap between energy supply and demand in Africa has been growing. Projections by experts in the field forecast that this gap will continue to grow, and the livelihood of more Africans will continue to be critically impaired by energy poverty, that will seriously slow down the socioeconomic development of the continent. Energy has been supplied in insufficient quantity, at a cost, form and quality that has limited its consumption by the majority of Africa's population, making the continent the lowest per capita consumer of modern energy of all regions of the world. The challenges are indeed daunting, and more than ever, a concerted effort by all actors is required to achieve any significant progress."

Given this challenge, the report sees a relatively promising future for renewable energy supplies and, equally importantly, increased energy efficiency, provided the energy supply sector is liberalized (as in Europe) to encourage private enterprise. The timing of such a change is assisted by an increased urgency to encourage sustainable development and combat climate change, and the growing availability of new technology (p 8).

Currently, fuel-wood is used throughout Africa as renewable energy, there is large and well-established hydropower capacity across the continent and geothermal power generation is established in the Rift Valley of Kenya. Apart from such "established" energy supplies, "new" technologies that have been commercialized worldwide in the last 30 years include wind turbine electricity, solar photovoltaic electricity, small hydro plant, and a wide range of secondary biofuels. Especially in North Africa, there is considerable expectation of relatively large scale generation of electricity from solar photovoltaic.[81]

Nevertheless, to date in Africa, most experience of the new renewables relates to small-scale installations, especially for stand-alone rural electricity. The potential is very large, but

[81] The environmental impact of large-scale solar installations in the Sahara is not discussed.

there are few African countries with comprehensive legislation to link liberalization of national utilities with increase of renewable energy from local and national resources (p 16).

Basically, energy supply is needed for heating, transportation fuel and electricity. Within each category, a range of renewable energy technologies has become reliable and cost-effective, and accepted for successful business and industry. Examples are: (p 18)

- Heating: solar water heaters, passive solar building design (also incorporating cooling), biomass crops and waste, biogas, geothermal sources, heat pumps.
- Transportation fuel: bioethanol and biodiesel, the latter based on feedstock such as sunflower, canola, and coconut. South Africa has a program to produce bioethanol from fermentation of molasses as a by-product of the sugar cane industry (using the by-product bagasse as fuel), and from fermentation of yellow maize. It will also produce biodiesel from palm oil and jatropha. [82] (p 19)
- Electricity: solar photovoltaic, wind, hydro (including run-of-the-river), geothermal, biomass thermal generation, biofuel engine generators.

The report notes that Africa has not to date introduced much clean technology despite the potential for doing so, and energy efficiency remains low. "The crux of the matter for Africa is that energy supplies are in practice limited and very expensive in proportion to available income. It makes sense to improve the energy efficiency, so costs reduce and productivity increases." (p 15) It lists many opportunities regarding heating, transport and other applications of energy supply, not only in improving the efficiency of supplying energy, but also improving the efficiency of the use of the energy – end-use efficiency (pp 21-24).

The report (Takada et al. 2007) is basically concerned with energy for electricity, heating and cooling, and transport as sustainable development options, rather than land management in the sense discussed in this background paper. The only reference to land use relates to the need for urban layout to benefit the types of transport that are important to the urban poor: walking, cycling, animal traction, and public transport (p 40).

Looking at Africa, especially Sub-Saharan Africa, provides an opportunity to view the issues from the least privileged part of the world. The issues change from country to country according to degree of development, geography, climate, population structure, poor versus more well-to-do and rural versus urban regions, and a host of other criteria. There would not be any nation, however, where land management issues are unimportant in the fight against climate change, and this would apply especially strongly to the poorest nations.

The recent publication of *Blue Carbon* provides a final but very timely reminder that the preservation of marine-based carbon sinks is as important as forestry and other terrestrial sinks. This includes Africa, where mangroves are prevalent on the east coast from Mozambique to Kenya, on the west coast of Madagascar, and along the Red Sea, and on the Atlantic side from Angola to Senegal. Seagrasses are found from South Africa to Somalia and northwest Madagascar, and more intermittently on the west coast from Nigeria to Ghana

[82] A perennial poisonous shrub originating in Central America but mainly grown in Asia and Africa, where it is used as a living fence to protect gardens and fields from animals. It contains an average of 34% oil, which can be processed to produce a high-quality biodiesel usable in a standard diesel engine (Wikipedia on *Jatropha curcas).*

and off Sierra Leone, Guinea, and the Canary Islands. Salt marshes are less prevalent, mainly occurring in South Africa and Angola (Nellemann et al. 2009, pp 36-37).

ADDENDUM: THE NATURE OF TECHNOLOGY

Brian Arthur's book (2009a) is important for understanding how technologies evolve, and therefore for understanding how future technologies may emerge. This note summarizes his thesis with a possible bias towards our scenario-planning purposes. An endnote outlines his three "laws", which are relevant for understanding the future of technology (Arthur 2004).

Arthur distinguishes between *individual technologies* ("technologies-singular") such as a jet engine or radar, and *domains* ("technologies-plural") such as electronics, radio engineering or biotechnology. *Invention* or *radically new technology* is also obviously important. How they link up is described below, but first we must note the inspiration from the two most quoted persons in his book: Charles Darwin[83] and Joseph Schumpeter.

COMBINATORIAL VERSUS BIOLOGICAL EVOLUTION

Technologies *evolve* in the sense that they all, including the novel ones called inventions, descend in some way from the technologies that preceded them. Arthur defines technological change as a organic process, giving it a living quality. Technologies are "ecologies" with components and practices that must fit together at any time, that change constantly as new elements enter, and throw off little sub-colonies from time to time that have a different quality. This provides a parallel to biological evolution, a link which according to "Arthur's Second Law" (see endnote) will strengthen in the 21st century.

In genetic evolution, new combinations are created in incremental steps which must produce a living organism at all stages. This does not work in technology. Schumpeter said in his *Theory of Economic Development* (1912, 1934): "Add successively as many mail coaches as you please, you will never get a railroad thereby." Rather, every novel technology and solution is a *combination* of parts from preceding technologies, facilitated by the constant capture and harnessing of natural phenomena that make the technology possible. In technology, Darwinian-type variation and selection happen when technologies are adapted to practical applications through engineering design, refining already formed structures.

Arthur acknowledges Schumpeter for the thoughts he first developed a century ago in his theory of economic development, discussed in Hoegh-Guldberg (2010c) under the heading *complexity theory and complexity economics*. The central concept is that economic development is an *endogenous* force, coming from *within* the economic system (Elliott 1983).

Schumpeter's theory that change in the economy arises from "new combinations of productive means" translates into "new combinations of technology" in modern terminology (Arthur 2009a, p 19). Schumpeter, of course, was almost alone among economists with his dynamic views on the integral role of technology. Arthur is one of a growing band of contemporary economists who have come to a similar view (no doubt aided by his polymath

[83] Arthur has written another overview (2009b) concentrating on demonstrating the difference between Darwinian evolution and the combinatorial evolution of technology ("evolution 2.0").

background in engineering, operations research, and complexity theory): “The overall collection of technologies bootstraps itself upward from the few to the many and from the simple to the complex. We can say that technology creates itself out of itself.” (p 21)

INDIVIDUAL TECHNOLOGIES

Individual technologies are means to fulfill a human purpose. The means can be processes or devices, which are the same thing at different levels: A technology embodies a series of processes – its “software”. These operations require physical equipment to execute them – its “hardware”. If we emphasize the software, we see a process or method. If we emphasize the hardware, we see a physical device.

Individual technologies are based on three principles:

1. C*ombination*: Every technology consists of parts organized around a essential idea that allows it to work. The primary structure consists of a main assembly that carries out the base function of the technology, and supporting subsystems.
2. *Recursiveness*: A technology consists of component building blocks that are themselves technologies, and these consist of sub-parts that are also technologies, in a repeating (recurring) pattern. These hierarchies can have several layers, all parts needing to be mutually compatible, which adds to the time and cost of developing new technologies.
3. *Phenomena*: A technology is always based on some phenomenon or phenomena that can be exploited and used for a purpose. Capturing phenomena is the basis of all physically based technologies, and helps explain their evolution: more sophisticated phenomena such as quantum effects could not have been uncovered without the prior discovery of the electrical phenomena.[84]

There are actually two types of “technology” in the sense that they represent means to fulfill a human purpose. Technologies such as radar or electricity generation are based on physical phenomena. But there is a huge range of other means of fulfilling human purposes such as business organizations, legal systems or contracts which are based on non-physical effects: organizational, behavioral, and even logical or mathematical procedures such as algorithms. These are also “technologies”, or at least first cousins within the class of *purposed systems.*[85]

Science is also a purposed system, and it is vitally important in the evolutionary process because science and technology co-exist, or “co-evolve”, in a symbiotic relationship. Modern science provides the formal uncovering of new phenomena and the understanding and knowledge of these phenomena. Technology builds from harnessing the phenomena which nowadays are being almost exclusively uncovered by science, but it also supplies the instruments and methods and experiments that science needs to develop its knowledge.

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[84] The dawn of electricity was in ancient Greece in 600 BC when one of the founders of Greek philosophy, Thales of Miletos, discovered the *phenomenon* that amber could be charged by rubbing (*electron* was the Greek word for amber). The Greek civilization itself could not have emerged without the prior evolution of primitive technologies based on fire, flint, and obsidian, and the technologies of the subsequent Neolithic revolution, which eventually enabled the city states of early recorded history to develop.

[85] Infrastructure is a related concept. Originally referring to public works from roads and bridges to schools and hospitals, it is now defined as the physical *and* organizational structure needed for a society or enterprise.

DOMAINS

As families of chemical, electrical, quantum or other phenomena are harnessed, they give rise to bodies of technologies that work naturally together (*domains*). They differ from individual technologies such as radar, which achieve particular purposes. A domain ("technology-plural") is a toolbox of useful components to be drawn from, a set of practices to be used. Domains are more than the sum of their individual technologies and operate in a different way from these. They determine what is possible in a given era, and what become the characteristic industries of an era. There is nothing static about this. What can be accomplished constantly changes as a domain evolves and as it expands its base of phenomena.

Engineers play an important role as designers of individual applications requiring new combinations of components to achieve a specific purpose. The specialized designs combine to push an existing technology and its domain forward. In this way, experience with different solutions and sub-solutions steadily accumulates and technologies change and improve over time. Engineering therefore makes important contributions to the evolution of technology and to future innovation.

THE ORIGIN AND DEVELOPMENT OF NOVEL TECHNOLOGIES

How do radically novel technologies arise – technologies using new or different principles for a particular purpose (the equivalent of new biological species)? Laser printing differs in kind from line printing technology, jet propulsion from propelled aircraft engines, and computation using electronic relay circuits from computation using electro-mechanic means. The new technologies use principles that are "radically novel" – they are *inventions*.[86]

A radically novel technology, however, *always* emerges from an accumulation of previous components and functionalities already in place. It is the culmination of a progression of previous devices, inventions, and understandings that led to the new technology. Supporting any novel device or method is an underlying *pyramid of causality*: of other technologies that used the principle in question; of antecedent technologies that contributed to the solution; of supporting principles and components that made the new technology possible; of phenomena once novel that made these in turn possible; of instruments, techniques, and manufacturing processes used in the new technology; of previous craft and understanding; of the grammars of the phenomena used and of the principles employed; of the interactions among people at all levels.

Particularly important in this pyramid of causality is the accumulated scientific and technical knowledge. It is contained within engineering itself, but also within universities, learned

[86] Brian Arthur focuses on this in *The Structure of Invention* (Arthur 2007). Schumpeter divided technological change into three phases: invention (the creation of new technologies); innovation (the commercial introduction of new technologies); and diffusion (the spreading of new technologies). Arthur noted that of these, invention has been by far the least studied and set out to remedy this in his paper. Like the other processes of technological change, invention raises its own challenges and problems, the solution of which may raise further challenges. As a result, invention is a recursive process: it repeats until each challenge or hierarchy of problems resolves itself into one that can be physically dealt with. It is a challenging process, usually lengthy, part-conceptual and part-experimental. It also typically involves many people and processes, so it is becoming difficult or impossible to name an individual originator of many modern inventions.

societies, national academies of science and engineering, and published journals. These form the critical substrate from which technologies emerge. Importantly, the logical structure for invention extends to origination in science; without the accumulated knowledge and capacity to innovate in science, the basis for technology would be vastly poorer.

Typically the initial version of a novel technology is crude and must be made reliable, scaled up and applied effectively to different purposes. As a technology develops, it runs into barriers and bottlenecks that are usually overcome by *replacing* the impeded components with more efficient components. This again leads to requirements to adjust other parts to accommodate it – it may even require a rethink of the architecture of the technology.

In addition to internal replacement, another mechanism of development is at work, which Arthur calls *structural deepening*. Here the component presenting an obstacle is retained, but additional components and assemblies are added to it to work around the limitation. By adding subsystems, technologies add "depth" and design sophistication to their structures as well as complexity.

The two mechanisms of development, internal replacement and structural deepening, apply through the life of a technology. Early on, a new technology is developed deliberately and experimentally. Later, it develops further as new instances of it are designed for specific purposes – it becomes part of the standard engineering process. But eventually there comes a time when neither component replacement nor structural deepening add much to performance. The technology reaches maturity. In the absence of a suitable novel principle, the old one gets *locked in.*

The locking-in of an older successful principle causes *adaptive stretch*. But at some point of development, the old principle cannot be stretched further. The way is now open for a novel principle to get a footing. The origination of a new principle, structural deepening, lock-in, and adaptive stretch, therefore have a natural cycle. Eventually the old principle is strained beyond its limits and gives way to the new one. The new base principle is simpler, but in due course it may become entangled itself.

THE DEVELOPMENT OF NEW DOMAINS

Many domains coalesce around a central technology. Computation spawned supporting technologies which might themselves develop into separate domains: printers, punched card readers, external memory systems, and programming languages. Other domains form around families of phenomena and the understandings and practices that go with these. Electronics and radio engineering were built on the understanding of electrons and electromagnetic waves.

A nascent field starts as part of its parent domain. Genetic engineering in its medical applications began as a minor offshoot of molecular biology and biochemistry. There is an experimental feeling about these early days; participants see themselves as solving particular problems in their parent domain. But in time, the new cluster acquires its own vocabulary and way of thinking.

Eventually domains reach old age. Some perish, but most live on: we still use bridges and roads, sewer systems and electric lighting, much as we did 100 years ago (though individual technologies within the domain develop, sometimes quite considerably like electric lighting over the past few years), but we still tend to take them for granted as technologies.

Not all domains go through a cycle of youth, adulthood and old age. Some disrupt the cycle by reinventing themselves every few years. They *morph* when one of its key technologies undergo radical change. Electronics changed character when the transistor replaced the vacuum tube. The communications and information technology domains keep morphing.

Besides morphing, a domain evolves new domains, often with multiple parentage. Information technology including the Internet is a child of telecommunications and computation, resulting from the marriage of high-speed data transmission and high-speed data manipulation. The parent fields live on, but they have birthed things that exist on their own, and now a good deal of their energy flows to the new branch. This tendency to morph and to sire new domains is part of what gives bodies of technology a living quality.

The economy adjusts when it encounters a novel body of technology. A new domain is described by its methods, devices, understandings, and practices. A particular industry consists of its organizations and business processes, production methods and physical equipment, all widely defined as "technologies". These two collections of individual technologies – one from the new domain, and the other from the particular industry – come together and influence one another, resulting in other new combinations.

IT ALL TAKES TIME

The unfolding of the new technology and readjusting of the economy takes a great deal of time. A revolution will eventually happen when the businesses and commercial procedures of the economy are arranged around its technologies, and these technologies adapt and become competitive on general compatibility and costs with other technologies that deliver similar benefits.

For this to happen, the new domain must gather adherents and prestige, find purpose and uses, resolve obstacles and fill gaps in its components, and develop technologies that support it and bridge it to the technologies that use it. Markets must be found, and the existing structures of the economy must be adjusted to make use of the new domain. The new domain must be recognized and the engineers who command the grammar of the old need to retool themselves for the new. All this must be mediated by finance, institutions, management, and government policies, and by developing skills for the new domain.

Domains therefore evolve differently from individual technologies. Once invented, the commercial development of a jet engine is basically focused, concentrated, and rational. Domains emerge slowly around loosely understood phenomena or novel technology, and build organically on the components, practices, and understandings that support these. As a new domain arrives, the economy encounters it and alters itself as a result.

"There is no reason that such evolution, once in motion, should end." (p 181)[87] But the process may take decades.

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[87] Arthur and Polak (2006) demonstrated technological evolution based on a simple computer model, in which the elements are common logic functions. Starting from a primitive technology, new circuits representing new

ENDNOTE: ARTHUR'S THREE LAWS

The Edge World Question Center[88] asks a different question each year which elicits 150-200 responses from prominent people with a wide range of skills and experiences. In 2004 it was "What's your law?" W. Brian Arthur came up with three "laws" which form an interesting background to his work on technology and provides an additional perspective on the future (Arthur 2004). Their subject matter figures in *The Nature of Technology*, though the treatment in the book doesn't immediately convey an impression that it should be elevated to the status of "laws". The prompt the question gave Arthur in 2004 to come up with some basic principles has therefore proved very useful.

Arthur's response is quoted verbatim.

Arthur's First Law: *High-tech markets are dominated 70-80% by a single player – product, company, or country.* The reason: Such markets are subject to increasing returns or self-reinforcing mechanisms.[89] Therefore an initial advantage – often bestowed by chance – leads to increasing advantage and eventually heavy market domination. (Absent government intervention, of course).

Arthur's Second Law: *As technology advances it becomes ever more biological.* We are leaving an age of mechanistic, fixed-design technologies, and entering an age of metabolic, self-reorganizing technologies. In this sense, as technology becomes more advanced it becomes more organic—therefore more "biological." Further, as biological mechanisms at the cellular and DNA levels become better understood, they become harnessed and co-opted as technologies. In this century, biology and technology will therefore intertwine.

Arthur's Third Law: *The modularization of technologies increases with the extent of the market.* Just as it pays to create a specialized worker if there is sufficient volume of throughput to occupy that specialty, it pays to create a standard prefabricated assembly, or module, if its function recurs in many instances. Modularity therefore is to a technological economy what the division of labor is to a manufacturing one—it increases as the economy expands.

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technologies are constructed by randomly wiring together existing ones and testing the result to see whether they satisfy any existing needs. If a circuit proves useful – satisfies some need better than its competitors – it replaces the one that previously satisfied that need. In the computer model it then adds itself to the active collection of technologies and becomes available as an element for the construction of still further circuits. So elements constantly add to the set of active technologies as they find uses, and leave again if rendered obsolete by others. In this way the collection of technologies bootstraps upwards by first creating simple technologies that satisfy simple needs, then from these more complex technologies to new ones that satisfy more sophisticated needs.

In several 250,000-step runs, the system evolved an 8-bit code, the basis of a simple calculator. Arthur (2009a, p 184) says that this would be impossible (one might say equivalent to the legendary monkey typing Shakespeare's plays by randomly hammering the keyboard) without the model creating a series of stepping-stone technologies first, which were then used as building blocks to create circuits of intermediate complexity to be finally used to create more complicated circuits. Arthur and Polak found that if they took away the intermediate mechanisms that called for these stepping-stone technologies, the complex needs went unfulfilled.

[88] http://www.edge.org/questioncenter.html.

[89] See the section on the Santa Fe Institute in Hoegh-Guldberg (2010c) on his development of dynamic models involving positive feedback from technological change (Arthur 1989, 1990).

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