GREEN ENERGIES

100% RENEWABLES BY 2050

MAE-WAN HO
BRETT CHERRY, SAM BURCHER & PETER SAUNDERS

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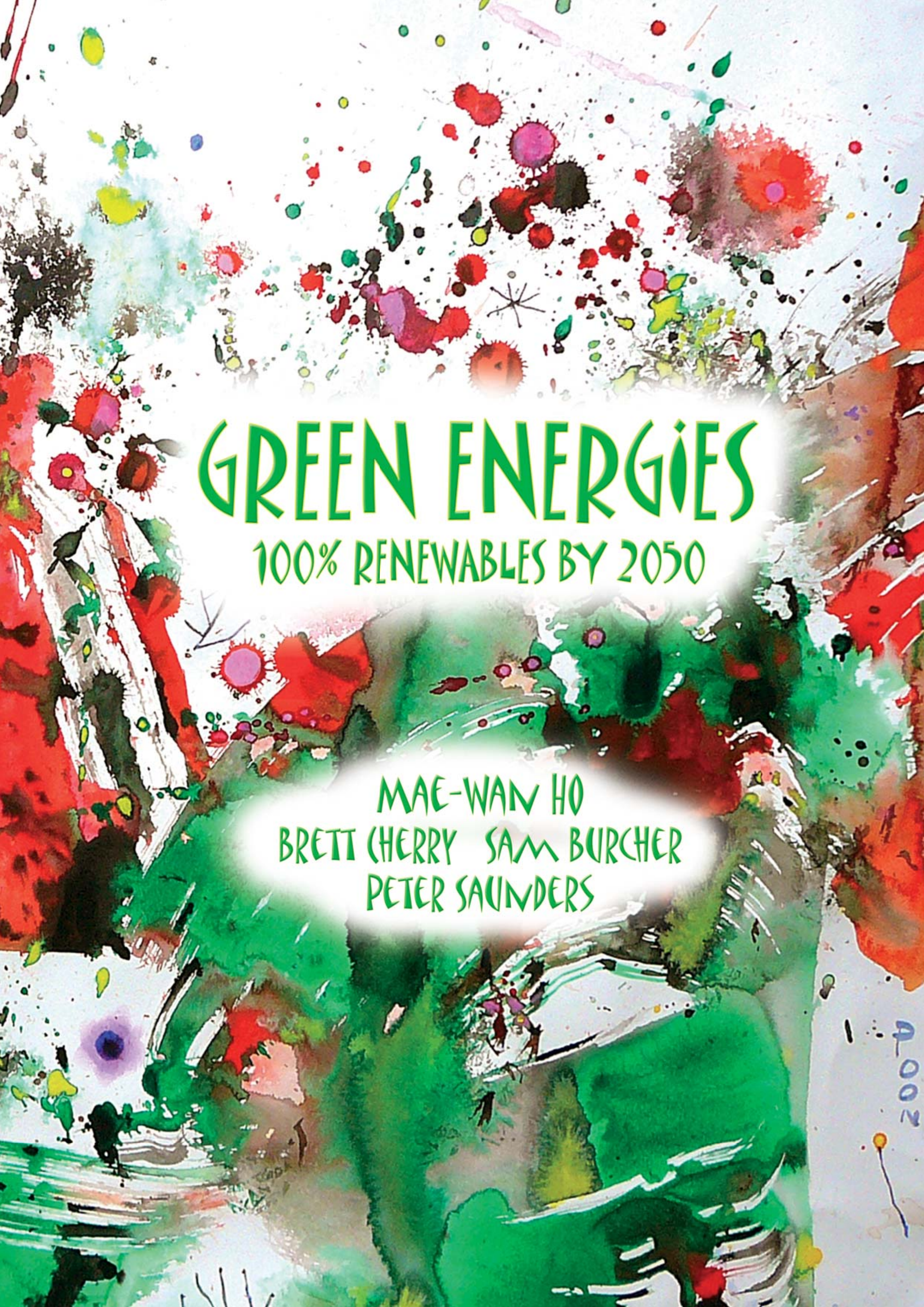
Institute of Science in Society
Third World Network



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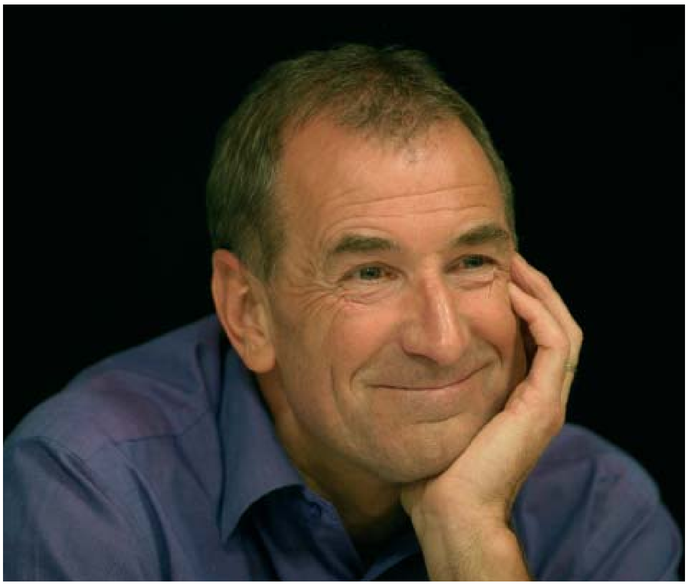
FOREWORD BY ALAN SIMPSON MP

Alan Simpson MP
UK Government Special Advisor on
Renewable Energy and Feed-in Tariffs



Let no one be in any doubt about the importance of this report. Take it seriously and this could be the 'get out of jail' card that Britain, and many other countries, will need to play in avoiding the drift into climate chaos.

The time for transformation is astonishingly short. There is no point in having 2050 targets without a programme that races into this transformation now. Rajendra Pachauri, the head of the International Panel on Climate Change, gives us three years in which to make dramatic switches in the whole way in which we think about energy systems.

Global leaders gathering in Copenhagen will haggle about a 2050 plan that can keep atmospheric carbon dioxide levels within a maximum of 450ppm. They hope it is not a bridge too far for the world's politicians. The difference between the politics and the science is that the real survival threshold is around 350ppm. We are already beyond this level. Tomorrow's agenda is not about the slowing down of carbon emissions, it is about how we row back form where we are now.

Many of the renewable energy choices set out in this report are already with us. Some require little more than a hop, skip and a jump to reach them. The trouble is that this leap has to be in a different direction from where we are currently heading. It involves some fundamental breaks from 'big energy', big pollution and the waste making society. Treading more lightly on the planet involves a shift into holistic economics which puts back as much - if not more - than we take out.

The report is a road map for survival. It sets out the science, the technology and the choices for a different future. All it requires is the political will… and that's where we're stuck. It invites changes that are as much about power as energy. Most of the choices touched on in the report work best where there is local and public ownership to ensure that the energy system supports sustainable communities rather than global shareholders.

It is not just about empowering the scientists to spell out what can be done. It is about empowering the public to become the drivers of change we can all live with. If we have the sense to act on this report may be we will.

FOREWORD BY CHEE YOKE LING

Chee Yoke Ling
Director
Third World Network

This report is an explosion of hope in a world caught in the morass of false and exorbitant solutions to the energy and climate crisis promoted by corporate interests.

The latest science alerts us that 350 ppm atmospheric CO_2 is the maximum limit that we must target in order to avoid "irreversible catastrophic effects". Developing countries with 80 percent of the world population - the vast majority struggling to rise above poverty - are already hard hit by more frequent and intense climate disasters, and any false solution foisted upon them will certainly stress them beyond the breaking point.

Fortunately, tremendous human capacity and technologies for real solutions to the crisis already exist, with more innovation emerging and further possibilities on the horizon, as *Green Energies* so clearly documents.

The challenge before us is to rapidly adopt renewable energies solutions across communities and nations. *Green Energies* is extremely timely as governments gather in Copenhagen in December 2009 to renew their commitment to fully and effectively implement the United Nations Framework Convention on Climate Change (UNFCCC) forged in 1992. It is our only legally binding global treaty on climate change, and nations small and large stated in the Preamble that they are "*Determined* to protect the climate system for present and future generations."

Equity is a pillar of the necessary transformation towards climate stabilization and sustainable development is enshrined in the UNFCCC. It was agreed that "the largest share of historical and current global emissions of greenhouse gases has originated in developed countries, that per capita emissions in developing countries are still relatively low and that the share of global emissions originating in developing countries will grow to meet their social and development needs."

Thus it was acknowledged that "the global nature of climate change calls for the widest possible cooperation by all countries and their participation in an effective and appropriate international response, in accordance with their common but differentiated responsibilities and respective capabilities".

Green Energies clearly states: "For the human species, it is the capacity to use natural resources responsibly and *equitably*, to meet the needs of *all* in the present without compromising the ability of future generations to meet their own needs."

It challenges governments to take a bold step in setting a national target for 100 percent green, renewable energy sources by 2050 that the report shows is possible with the right policies and global cooperation in place. The report is inspiring and realistic. We *can* do it, and cannot *not* do it. Climate and our survival are non-negotiable.

PREFACE

350 PPM THE NEW TARGET

Global warming is happening much faster than the IPPC (Intergovernment Panel on Climate Change) predicted in its latest 2007 report. For one thing, Its climate models failed to account for the rapid summer melting of the polar ice caps that's been making headlines several years in a row.

The IPCC helped set the 450 ppm maximum of atmospheric CO_2 that is supposed to limit the global temperature rise to below 2 ˚C, and prevent "dangerous anthropogenic interference with the climate system."

But top climate scientists Jim Hansen and colleagues, using more realistic climate models and key data from the remote history of the earth, showed that 450 ppm is beyond the danger zone, and we must even reduce atmospheric CO_2 down from its 385 ppm to 350 ppm, or else face "irreversible catastrophic effects" [1]. The head of IPCC Rajendra Pachauri now agrees [2].

The good news is that we can still do it. It is not too late. All it takes is to stop burning fossil fuels to bring atmospheric CO_2 back down to 350 ppm within the next decades. But we must act now, because 385 ppm is already within the danger zone, and we cannot afford to let it remain there for too long, or we push the planet past the point of no return.

That is why we need to commit ourselves to truly green energies as a matter of urgency

WHAT'S TRULY GREEN?

'Green' is environmentally friendly, healthy, safe, non-polluting, renewable, and sustainable.

Renewable energy, as defined by British Petroleum (BP) [3], is derived from natural processes that do not involve the consumption of exhaustible resources such as fossil fuels and uranium. But it could include industrial scale biomass, biofuels, or hydroelectric from large dams, none of which is sustainable.

'Sustainable' is the key to being truly green. But the word 'sustainable' has been hi-jacked so often to mean just the opposite that it needs to be redefined.

To be sustainable is to endure like a natural biodiverse ecosystem for hundreds if not thousands of years, thanks to a circular economy of cooperation and reciprocity that regenerates and renews the whole [3]. For the human species, it is the capacity to use natural resources responsibly and *equitably*, to meet the needs of *all* in the present without compromising the ability of future generations to meet their own needs. We have updated the usual Bruntland definition of sustainability [4] to incorporate the overriding lesson from nature that cooperation and reciprocity between the biodiverse inhabitants of the ecosystem are necessary for the survival of the whole; and this applies all the more so to ecosystem Earth.

Unfortunately, our policy-makers are by and large still engaged in confrontational politics, being misled by the Darwinian myth of competition and the survival of the fittest that will surely take us beyond the point of no return. History has taught us why civilisations collapse in the past when faced with ecological crises [5], simply through the failure to take the political decisions necessary for survival. Are we going to repeat history in the present global ecological crisis that has the survival of the entire human species at stake? Or will our political leaders in the United Nations Framework Convention on Climate Change learn to cooperate and adopt the most appropriate green energy policies for us to meet the 350 ppm target?

As Germany has demonstrated so well within the past decade, the appropriate policies can trigger a dramatic growth in new renewable energies, with industry offering a variety of distributed, decentralised options that also give people autonomy and independence from big centralised power stations. The global shift to renewable energies is happening, and many politicians and energy experts see no difficulty in producing a 100 percent of our energy from renewable sources by 2050, which is what Germany intends to achieve [6], as the world's first major renewable economy.

Green Energies is a follow up on *Which Energy?*, the first in the series of ISIS' Sustainable World Initiative reports, and an elaboration of the theme of local food and energy systems presented in *Food Futures Now, Organic, Sustainable, Fossil Fuel Free*, the second report in the series.

Green Energies provides policy-makers and the public with the evidence for making the right decisions that will enable us to meet the 350 ppm target and 100 percent renewable energies by 2050. Time is running out, as are remaining resources. That's why it is important at the outset to recognize and reject options that are neither renewable nor sustainable *are* dangerous, notably nuclear, carbon capture and storage, and biochar. Our capacity for truly sustainable and renewable energies is growing every day. It is neither necessary nor acceptable to export the burden of cutting carbon emissions to poor developing countries via carbon trading schemes. The developed nations must take responsibility for reducing their own emissions at home, while providing genuine financial and technological assistance to poor nations that have to cope with the worst effects of climate change.

Renewable energy is inexhaustible energy. Wind energy alone can supply 40 times the world's electricity use or its total energy consumption five times over. An enormous potential also exists for solar energy, and electricity from locally installed solar panels is already as cheap as electricity from the grid. People everywhere are innovating and switching to renewables to save on fuel bills and saving communities as they are saving the planet. In 2008, for the first time, more renewable energies capacity has been added than conventional energies and the trend continues. Local small scale and micro-generation are booming in the developed countries wherever feed-in tariffs have been introduced, giving people independence and autonomy, plus the flexibilities for upgrading as technologies improve.

At the same time, appropriate science at the frontiers has opened up new possibilities for recycling waste heat as electricity, harvesting and storing sunlight by artificial photosynthesis, and solving our nuclear waste problem by low temperature transmutation after we give up nuclear energy for good. These are exciting times. All we need to save the planet is for our leaders follow the way of nature and the will and wisdom of the people.

Mae-Wan Ho and **Peter Saunders**

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AUTHORSHIP & ACKNOWLEDGMENT

Brett Cherry wrote Chapters 15, 16 and 17, and contributed to Chapters 1 and 13. Sam Burcher wrote Chapters 19, 20 and 23, and contributed to Chapter 22. Prof. Peter Saunders wrote most of Chapter 1, co-wrote Chapter 2 with Dr. Mae-Wan Ho, and co-edited the volume. Chapters 34 and 35 are assembled from previous articles written by Lewis Larsen of Larttice Energy LLC and edited by Dr. Mae-Wan Ho. Prof. Joe Cummins wrote Chapter 24 and co-wrote Chapter 26 with Dr. Mae-Wan Ho. Peter Bunyard wrote Chapter 25. Prof. Li Kangmin co-wrote Chapter 21 with Dr. Mae-Wan Ho. The rest were written by Dr. Mae-Wan Ho, who also edited the volume with Prof. Peter Saunders.

Andy Watton was responsible for design and production, Sam Burcher for publication, print and distribution, liaising with sponsors, and organizing the launch conference, and Julian Haffegee and Brett Cherry for other support.

Most of the artwork in this volume has been generously donated by a member of ISIS' Board of Trustees, Canadian artist Li Poon, much acclaimed for his unique style and "shamanistic" qualities. His most recent paintings can be seen at http://lipoon.wordpress.com.

All except Chapters 1, 2, 11, 13, 17, 18, 20 and 23 (which are new) are based on articles that have appeared in past issues of *Science in Society* and updated, and revised to varying degrees, having benefited from feedback from our readers.

We thank the numerous scientists who check the accuracy of our description of their work in different chapters and gave us useful comments and suggestions. The deficiencies that remain are entirely our own.

We are especially grateful to Chee Yokeling and Alan Simpson for their enthusiastic response to the report and for key input.

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EXECUTIVE SUMMARY & RECOMMENDATIONS

GREEN ENERGY OPTIONS FOR ALL

The world is shifting to renewable energy in the wake of peak oil and accelerating global warming. In contrast to the exhausting supplies of fossil and nuclear fuels, renewable energy is inexhaustible.

But being renewable is not enough. It must also be environmentally friendly, healthy, safe, non-polluting and sustainable. 'Green' energy encapsulates all of these qualities, of which the most important perhaps is 'sustainable'. 'Sustainable' needs to be redefined at the outset to counter its widespread misuse to mean just the opposite.

To be sustainable is to endure like a natural biodiverse ecosystem for hundreds and thousands of years through a circular economy of cooperation and reciprocity that regenerates and renews the whole. For the human species, it is the capacity to use natural resources responsibly and *equitably*, to meet the needs of *all* in the present without compromising the ability of future generations to meet their own needs. The overriding lesson from nature is that cooperation and reciprocity between the biodiverse inhabitants of the ecosystem are necessary for the survival of the whole; and this applies all the more so to ecosystem Earth.

This report shows that a wide variety of truly green and affordable energy options already exist for all nations to become energy self-sufficient and 100 percent renewable within decades. Policies and legislations that promote innovations and internal market, and decentralised, distributed small to micro-generation are the key.

100 PERCENT RENEWABLE BY 2050 TRANSITION TO LOW CARBON AN OPPORTUNITY

Transition to a low carbon or zero carbon economy is a matter of urgency especially for the developed nations that are also the major emitters of greenhouse gases.

It is generally assumed that transition to low carbon is an economic hardship that should be avoided as far as possible. But as Germany has clearly demonstrated, it can be an unprecedented opportunity for innovations, for creating new jobs and new markets, and delivering health and wealth to the nation.

Germany has stolen a march on the rest of the world in research and development of renewable energies since the last oil crisis of 1974. Within the past two decades, the government has provided subsidies and important legislations to create an internal market, the most important of which is the Feed-in Law, first introduced in 1991, and in a modified form in 2000, which obliges national utilities to buy electricity generated from renewable sources at above-market rates set by the government.

As a result, Germany now generates 7.3 percent of its primary energy from renewable sources: 29 GW of wind energy, 13.5 GW in photovoltaic (PV), 7.3 GW in solar thermal, the rest in hydroelectric, geothermal and biomass, as appropriate to resources available in the country. The government is committed to increasing the proportion of renewable energy to 50 percent by 2050, but its renewable industry claims it can do three times as well to reach 100 percent renewable by that date.

There is no provision for nuclear energy in Germany's low/zero carbon future; it is to be phased out completely by 2022. Carbon capture and storage does not figure up to 2020, as even its supporters do not expect it to be commercially available by then.

Germany is also to reduce greenhouse gas (GHG) emissions by 40 percent from their 1990 levels by 2020. And it is not counting on carbon trading to export its GHG emissions to developing countries and increase their burden.

In contrast, the UK Government's Low Carbon Transition Plan is a lackluster, business-as-usual paper exercise, consistent with its failure to stimulate and support renewable energy options over the years. The UK's renewable energy contribution is currently about 1.8 percent, third from bottom in the European Union league table, ahead of Malta and Luxembourg. The government has also opted to depend on a nuclear industry that has already become a financial and safety nightmare, and on carbon capture and storage, an untried technology that will entrench the nation in fossil fuels. Worse yet, it will rely on carbon trading to export GHG emissions to developing countries.

THE NUCLEAR BLACK HOLE

The much touted "nuclear renaissance" promoted by Ppresident George W Bush and other governments is unravelling. Across the USA, the nuclear power industry has so far failed in its efforts to overturn any state ban on building more reactors. The Obama administration put a freeze on Yucca Mountain as a long-term nuclear waste deposit in February 2009 amid new evidence of runaway construction costs.

The nuclear industry is notorious for cost overruns during construction of power plants. But that is nothing compared to the downstream costs of decommissioning, waste management and disposal. It is considered a bad investment for private industry. Consequently, the UK taxpayer has had to take over all liabilities and costs of running the dirtiest, loss-making parts of the industry at Sellafield, now £3 billion a year and rising. Meanwhile the cost of clean-up and decommissioning has ballooned to over £73 billion. Sellafield has become the world's nuclear waste dump with no end in sight, its reprocessing plants are not functioning and there is as yet no designated final waste repository as more spent nuclear wastes pile up.

As one commentator remarked of the US industry: "Rarely has so much money, scientific know-how and raw state power been marshalled to achieve so little." Several hundred billion dollars of investment resulted in 104 operating plants, about a quarter of the global total that produces just 19 percent of electricity in the country. The cost of nuclear waste disposal was last estimated at US$96.2 billion.

The US taxpayer too, was left with enormous burdens in "stranded costs", while the nuclear industry in both countries continue to milk the old reactors for sheer profit, well past their decommissioning dates, and often their safety limits.

Adding to the hundreds of billions already squandered are an estimated US$1 trillion in research and development that governments around the world have spent on 'safer', 'cleaner' reactors that have proven fruitless so far.

Safety is a major issue. It turns out that none of the existing reactors or even 'generation 3' reactors under construction are proof against malfunction or sabotage. In addition, a main source of hazard is the spent fuel sitting in overcrowded cooling ponds on site that can easily catch fire and cause explosions.

The fallout from Chernobyl was 30 to 40 times that released by the atom bombs of Hiroshima and Nagasaki in Japan during World War II. A 2005 report estimated it was responsible for 56 direct deaths, and an estimated 4 000 extra cancer cases among the approximately 600 000 most highly exposed, and 5 000 among the 6 million living nearby.

There is also strong new evidence from Germany linking childhood leukemia to proximity to nuclear power stations, which gives a hint of the health burden of accumulating toxic and radioactive wastes to present and future generations.

Globally, nuclear power contributed to14.8 percent of electricity and a mere 2.1 percent of energy consumed in 2006, and falling since; in the meantime, the world's new renewable energy contribution has risen from 0.4 to 6.2 percent. To put nuclear power in perspective, Germany in a single year of 2007 increased its renewable energy output by 15 TWh, the equivalent of two nuclear reactors.

High grade uranium ore is fast depleting, and mining and extracting uranium is energy intensive as well as environmentally destructive. Lifecycle assessments show that when uranium ore grade falls below 0.02 percent in the next 50 or 60 years, it would consume more energy to build uranium fuel reactors than the energy they could ever produce.

It is obvious that we must abandon the nuclear option as quickly as possible and concentrate on installing renewable energy generators. It takes only a few days to install wind turbines or solar generators, while a nuclear power plant takes an average of 10 years or more.

Meanwhile, as part of global nuclear disarmament, high weapons grade uranium could be burnt up in the remaining nuclear reactors. At the same time, serious investments should be made into condensed matter nuclear science that could transmute toxic and radioactive nuclear wastes into safer elements while generating more energy (see later).

BEWARE THE BIOCHAR INITIATIVE

We warned against biofuels from 'bioenergy' crops and plantations in our 2006 *Which Energy?* report and predicted the increased deforestation, land grab and food price hikes that have come to pass. Calls for moratorium on biofuel plantations have now come from Africa, the United Nations, the US, and the UK government's Environment Audit Committee.

The International Biochar Initiative (IBI) is similar in that it proposes is to grow crops and trees on hundreds of millions of hectares of illusory 'spare land' in Africa, South America South Asia, and other developing countries. But instead of making biofuels from the harvested biomass, it will be turned into biochar (charcoal) to be buried in the soil, where it will remain stable for thousands of years and increase crop yields. Biochar is therefore promoted as a "carbon negative" initiative that could save the climate – by sequestering stable carbon in the soil - and boost food production. The industrial 'pyrolysis' process that produces biochar could also recover some low grade fuels as by-products.

IBI is strongly criticised as a "new threat to people, land and ecosystem" in a declaration signed by more than 155 non-profit organisations worldwide.

The IBI was inspired by the discovery of 'terra preta' (black earth) in the Amazonian basin at sites of pre-Columbian settlements (between 450BC and 950 AD), made by adding charcoal, bone, and manure to the soil over many, many years. According to local farmers in the Amazon, productivity on the terra preta is much higher than surrounding soils.

But biochar produced today is not terra preta, as research findings have indicated. Furthermore, buried biochar is not stable, and could also increase the breakdown of humus in the soil. At the same time, its ability to improve crop yields appears sporadic, short-lived, and dependent on local conditions.

Most of all, saving the climate is not just about curbing the rise of CO_2 in the atmosphere that can be achieved by burying stable carbon in the soil (or CO_2 in the ground in case of carbon capture and storage), it is also about keeping oxygen (O_2) levels up. Keeping O_2 levels up is what only green plants on land and phytoplankton at sea can do, by splitting water to regenerate O_2 while fixing CO_2 to feed the rest of the biosphere. Climate scientists have only discovered within the past decade that O_2 is depleting faster than the rise in CO_2 both on land and in the sea. The acceleration of deforestation spurred by the biofuels boom since 2003 appears to coincide with a substantial steepening of the O_2 decline. In addition, biochar itself is an oxygen sink in the course of degrading in the soil; adding to the depletion of oxygen that cannot be regenerated because trees have been turned into biochar for burial. If biochar is promoted under the Clean Development Mechanism, it will almost certainly further accelerate deforestation and destruction of other natural ecosystems (identified as 'spare land') for planting biochar feedstock. All that will swing the oxygen downtrend that much closer towards mass extinction. And humans may be among the first to go, given our high oxygen requirements.

CARBON CAPTURE & STORAGE

Carbon capture and storage (CCS) is intended to reduce the impact of burning fossil fuels by capturing CO_2 from power stations and storing it underground in depleted oil and gas reservoirs, disused mines or deep saline aquifers. CCS has wide support among governments as the world oil supply is failing to meet demand and many countries still have large coal reserves.

CCS is an unproven technology. Its earliest commercial deployment is not expected before 2030, which would make it too late to be of use. The International Energy Agency estimates that for CCS to deliver any meaningful climate mitigating effect by 2050, 6 000 projects each injecting a million tonnes of CO_2 per year into the ground would be required.

CCS uses up between 10 and 40 percent of the energy produced in the power station, thereby erasing the efficiency gains of the last 50 years and increasing fuel consumption by one third. Power stations with CCS also require 90 percent more fresh water than those without. CCS is expensive and could double the plant costs and increase the price of electricity by 21 to 91 percent. A recent study commissioned by the German federal government confirmed that compared with renewable energy options such as wind and solar, CCS will increase CO_2 emissions 10 to 40 fold and raise the cost of electricity by 100 percent

The efficacy and safety of CO_2 storage is very much in doubt. A 2006 US Geological Survey pilot field experiment in a saline sedimentary rock formation in Frio, Texas, found that the buried CO_2 dissolved large amounts of the minerals in the rocks responsible for keeping the gas contained, thereby releasing CO_2 into the air. To be viable, the CO_2 captured and stored must leak at a globally averaged rate of not more than one percent per year over a timescale of centuries; otherwise, the emitted flux will be greater than or equal to that intended to be mitigated initially.

WORLD SHIFTING TO RENEWABLES

In 2008, for the first time, more renewable energy than conventional power capacity was added in both the European Union and United States, and the trend is continuing. Global power capacity from new renewable energies (excluding large hydro) reached at least 280 GW in 2008, a 16 percent rise from the 240 GW in 2007. New renewable energies now account for 6.2 percent of the global formal power sector capacity. This does not include, for example, the rapidly growing household generation of biogas in China, estimated to have reached 9 GW at the end of 2008, and is in addition to the traditional renewable of large hydroelectric that accounts for 6 percent, and fuel wood and other biomass in poor households, estimated at 12 percent.

Solar tops the new renewable energies. Solar heating capacity increased by 15 percent to 147 GW. Solar hot water in Germany set record growth in 2008, with over 200 000 systems installed, taking its total capacity to 7.3 GW. Grid-connected solar photovoltaic power continued to be the fastest growing power generation technology, with a 70 percent increase globally to reach 13.4 GW.

Global wind power capacity grew by 28 GW in 2008 to 122 GW. This was the fifth consecutive year of accelerating growth at just over 28 percent per annum. The US led the growth with 8.4 GW, a 49.5 percent increase on 2007; while China came second with the fastest growth rate and the second highest capacity increment at 6.2 GW.

At least 73 countries had renewable energy policy targets by the end of 2008, and several more were added to the list in 2009.

Feed-in tariffs were adopted in at least five countries for the first time in 2008 and early 2009: Kenya, the Philippines, Poland, South Africa and Ukraine.

Many politicians and renewable energy experts in Europe see a realistic option of 100 percent renewable energy supply in a commercial market free of any subsidy by 2050. The key is decentralised, distributed generation that provides energy autonomy at the point of use, a model that has proven so successful in Germany.

WHY & WHICH RENEWABLES?

The electricity industry contributes 37 percent of the world's carbon emissions, predominantly from burning fossil fuels. Renewable energies such as solar and wind do not emit CO_2 while generating electricity, and have the further advantage of improving the efficiency of energy use considerably.

Big power plants are located far away from most users, so the electricity generated has to be transported long distances over power lines where more than 7 percent may be lost before it is used. In addition, some 60-70 percent of the energy is lost as 'waste' heat. In contrast, solar panels and wind turbines are readily installed on or near homes and farms and the electricity generated as well as the heat can be consumed directly without much loss. Furthermore, because the capital costs of installation are much lower, they can be easily be upgraded to take advantage of technological improvements.

A 'cradle-to-grave' life-cycle assessment (LCA) gives a clearer idea as to how much better off we are with renewable electricity generation, and how different renewable options compare with one another. LCA includes upstream processes such as mining, refining, transport and plant construction, the production of the device or equipment, the generation and distribution of electricity, and downstream processes such as decommissioning and disposal of wastes.

Convenient measures are energy payback ratio, *EPR*, the energy produced during the operational lifetime *versus* total energy spent in LCA, and the amount of CO_2 produced per unit of energy in g CO_2/kWh.

Currently, small hydroelectric power tops the list with EPR 30-267 and 4-18 g CO_2/kWh; wind comes next at EPR 18 and 16.4 g CO_2/kWh offshore, and EPR 34 and 9.7 g CO_2/kWh onshore. Photovoltaics (PVs) come third at EPR 6-9-and 44-217 g CO_2/kWh. These performance parameters are clearly far superior to conventional oil or coal-fired plants.

Interestingly, modern combined cycle fossil fuel plants already perform as well or better than a conventional boiler plant fitted with carbon capture and storage.

PVs are improving rapidly; a 2008 study on 11 types of PV panels gave greenhouse gas emissions of 26 to 55 g CO_2/kWh, with CdTe (cadmium telluride) thin film PV modules clearly ahead with the lowest emissions of GHG as well as nitrogen oxides and sulphur oxides. But concerns remain over the high toxicity of components such as Cd, particularly if large numbers of such panels are to be fitted in earthquake zones. Efforts should be made to substitute safer alternatives in the fabrication of PVs as these are becoming common household fixtures.

SOLAR POWER TO THE PEOPLE

It is estimated that with a modest 10 percent efficiency at capturing solar energy, less than 0.1 percent of the earth's surface covered with solar panels would satisfy all the world's energy needs. Rapid technological improvements and savings from distributed local small scale and micro-generation could easily reduce the required area by an order of magnitude.

By far the greater capacity of solar power is in solar thermal that harnesses solar energy for heating, cooling, or producing electricity. However, solar photovoltaic (PV) - capturing sunlight to generate electricity directly - has undergone exponential growth since 2002, and is now the faster growing solar sector

Ease of manufacture and installation, modular design that could make use of any exposed surface such as roofs and walls, maximum flexibility, and minimum intrusion and maintenance, all contribute to the success of solar power. Solar power has topped the world's renewable energies capacity at least two years running and is set to grow further as China and India have entered the market and are offering strong competition to Germany, and stimulating further innovation.

Solar PV especially is improving by leaps and bounds. Thin film technologies have brought down the price of PV panels and solar electricity is competitive with electricity from the grid in the highest-priced markets in the developed world. Although less efficient, thin film PVs more than compensate for that in being much cheaper and easier to manufacture.

'Third generation PVs are boosting efficiency while maintaining the cheaper manufacturing techniques of thin films. One example is quantum dots, nanometre size particles that improve efficiency by extending the band gap of solar cells for harvesting more of the solar spectrum and by generating more charges (and hence more electricity) from absorption of a single photon. Using quantum dots mixed with semi-conductor printed onto a highly conductive metal foil, one company has achieved a module efficiency of about 12 percent at a cost of US$0.3/watt. The company plans to sell these modules at US$1.0/W which makes them currently the cheapest solar panels on the market.

Another strategy to increase efficiency is to use light tracking lenses and non-imaging optics to concentrate sunlight onto solar cells, thereby decreasing the size of solar cells required. A record efficiency close to 40 percent has been reached in the laboratory. New light concentrator based on light absorbing organic dyes could cut costs down substantially.

A third strategy is to use transparent thin films that are also conductors of electric charge, allowing light to pass through to the light absorbing material beneath and serving as an electrical contact to transport charge carriers away from the light absorbing material, thereby increasing the efficiency.

Other current approaches include quantum wells, which trap electrons and holes (separated charges) in two dimensions, preventing them from recombining, and effectively increasing the gain and efficiency of solar cells. Organic solar cells using organic polymers mixed with fullerenes (carbon nanostructures) have achieved a solar cell efficiency of 6.5 percent. Their main advantage is being flexible and light weight, and can be made transparent to be used on windows for urban buildings, for example. Successive layers absorbing in different parts of the spectrum could be placed one on top of the other by a printing process, and further improvements in efficiency are on the cards, though major obstacles remain in the longevity of these solar cells.

WIND ELECTRIFIES THE WORLD 40 TIMES

A study based on state-of-the-art data combined from multiple sources and computer simulation shows that wind turbines on land restricted to ice-free, non-forested, non-urban areas operating at as little as 20 percent of their rated capacity could provide more than 40 times the world's current electricity consumption, or over five times its total energy needs.

Wind power is on a steep ascent. It accounted for 42 percent of all new electrical capacity added to the US in 2008. The Global Wind Energy Council projected a 17-fold increase in wind-powered electricity globally by 2030.

The ten biggest CO_2 emitting countries in the world – US, China, Russia, Japan, India, Germany, Canada, UK, South Korea and Italy – all have far more than enough potential from wind to power their electricity needs: 18 times for China (89 percent from land), 23 times for the US (84 percent from land) and 30 times for the UK (41.5 percent from land).

Wind power is coming to Africa. Plans are afoot to build Africa's largest wind farm in the desert land around Lake Turkana in Kenya, 70 percent of the funds, €300 million coming from the African Development Bank. The Lake Turkana Wind Project consists of 365 wind turbines each 30-40 m high with a capacity of 850 KW. When complete, it will add about 25 percent to Kenya's existing electricity capacity. The Tigray region of neighbouring Ethiopia recently commissioned a £190 million wind farm, representing 15 percent of Ethiopia's current electrical capacity. In Tanzania, 100 MW power will be produced from two projects in the Central Singida region, which accounts for more than 10 percent of the current supply. Two further wind projects are underway in Kenya. One is in the popular tourist town Naivasha and one is in the Ngong Hills near Nairobi where Danish wind company Vestas have already installed six 50-metre V52 turbines contributing 5.1 MW to the national grid.

Earlier in 2009, South African became the first African country to announce a feed in tariff for wind power

However, more than 20 percent of Africans do not have access to electricity, and extending the grid does not help the poorest. What they need is local power.

Local micro-generation of wind power is eminently feasible. In the UK, micro wind electricity generation is increasingly popular for households and commercial buildings. UK's Department for Business Enterprise and Regulatory Reform (BERR) runs a Low Carbon Buildings Programme that provides grants for micro-generation technologies including wind turbines and solar power for householders and public building.

The current cost of micro wind generation is still rather high, but it could come down considerably. William Kamkwamba from a remote village in Malawi built his first wind turbine from scrap when he was 14 years old, and Max Robson in the UK has been inspired to produce an Envirocycle Scrap Wind Turbine prototype at £20 budget that he claims cost £2 000 on the market. Such low cost micro-generation options are particularly appropriate for developing countries.

A new low cost wind turbine has been invented using an induction motor as a generator. The high costs of wind turbines are due to custom-built generators, invertors, storage batteries and complex circuitry in order to fit in with the 60 cycles alternating current (AC) of the domestic electricity supply. The electricity generated by using an AC inductor motor is not at constant voltage or frequency, but hot water tanks heater elements don't mind variable voltages or frequencies; so the electricity generated by the wind-turbine is simply used to heat water. In addition, a patented electronic control acting like a gearbox ensures that the turbine aerofoils operate at peak performance at all time, so that all the power is harvested and channelled to the load, a heat exchanger tank, which heats the domestichot-water tank and also feeds surplus heat into the domestic central heating.

BIOGAS ECONOMY ARRIVING

Biogas is a combustible mixture of gases produced in anaerobic digestion by micro-organisms of livestock manure and other biological wastes. The major constituents of biogas are methane (CH_4, 60 percent or more by volume) and carbon dioxide (CO_2, about 35 percent), with small amounts of water vapour, hydrogen sulphide (H_2S), carbon monoxide (CO), and nitrogen (N_2). . Biogas is used as fuel, like natural gas, for combined heat and power generation, while the digested mixture of liquids and solids is mainly used as organic fertiliser for crops. When upgraded and purified, biogas methane can be used as fuel for cars and farm machinery, producing much less particulates and other toxic substances in its exhaust than fossil fuels. Another major advantage of anaerobic digestion is that it prevents at least 90 percent of the environmental pollution from agricultural and industrial wastes.

We have been promoting anaerobic digestion since 2005 for recycling wastes into resources in an integrated food and energy 'Dream Farm 2' that, if universally adopted could cut more than 50 percent in energy consumption and GHG emissions.

We are gratified that anaerobic digestion has grown substantially since. In China, the original home of anaerobic digestion, the number of biogas digesters increased from 17 million in 2005 to 26 million in 2007, and an estimated 31 million at the end of 2008, equivalent to 9 GW of renewable energy, mostly in small rural households.

Biogas is booming in Germany and has become Europe's fastest growing renewable energy sector. Unfortunately, biogas production in Germany has relied to a large extent on energy crops such as maize. Big companies are involved in building gigantic biogas digesters and developing biogas refineries that clean the resulting biogas to produce pure methane to be fed into the natural gas grid.

Sweden pioneered the use of biogas methane as vehicle fuel in the 1990s with strong government support. By 2006, 54 percent of the gas delivered to vehicles was biogas methane. By June 2007, there were 12 000 vehicles driving on biogas methane and 500 filling stations and 70 000 vehicles are expected by 2010. In June 2009, a new plant was announced in Stockholm that will supply the capital with bio-methane both as vehicle fuel for buses and cars and for the new city gas grid. It will be the largest bio-methane plant in Sweden, producing 10.5 million m^3 bio-methane a year, doubling the production capacity in Stockholm, and constituting 31 percent of the Swedish market in 2008.

A conservative estimate for the USA indicates that biogas from livestock manure could generate between 68 and 108.8 TWh of electricity a year, or 1.8 to 2.9 percent of the country's electricity, at a saving of between 47.2 and 150.4 Mt of CO_2, about 1.9 to 6 percent of the country's GHG emissions.

There is, however, a danger that the biogas economy will be hijacked by big companies for centralised power generation from bio-energy crops, which may jeopardise our food security and prevent its full energy and carbon mitigating potentials and other benefits of distributed decentralised small scale generation from being realised.

A COMMUNITY PROJECT

A project based on a community cooker that burns rubbish is potentially capable of transforming the slums of Kibera, Kenya. The special cooker is the technical innovation of local, self-taught furnace-builder Francis Gwehonah, and is at the heart of a an award-winning project designed by Nairobi-born architect Jim Archer and implemented with the help of his Kenyan fellow Director Mumo Musuva and their Planning Systems Services team.

The cooker boils water, cooks vegetables, stews beef, bakes cakes, fries food, and has two ovens each large enough to grill a whole goat. The slum dwellers have solved several practical problems themselves. Volunteers from various local youth groups collect, sort and store the garbage in metal racks next to the cooker where it can dry. Materials that cannot be burnt such as rubber and glass are put to one side. Biodegradable scraps that fall through become compost manure. The useful solid waste material like paper and plastic - bags, drinks bottles and packaging - as well as food scraps from banana, cassava, maize cob and sugarcane, peel, sawdust and even the discarded carrier bags of human and animal excrement colloquially known as 'flying toilets' are forked up to the top level of the racks ready for incineration. All these items would normally be left to rot in the street, thrown into water courses, or dumped in local rivers.

The volunteers also suggested how they could be rewarded: they do the sorting for the public from say 6 am until midnight. But from midnight until 6am they work the cooker for themselves, making bread and buns and hot water that they sell during the day.

It costs 5 Kenya shillings or US$0.06 to make a family meal, much cheaper than the kerosene that would otherwise be needed. The cooker also heats water for communal washing. On average 50 people a day take hot water into the 'bafu' (bathroom) closet for washing, and as many as 200 people could wash from the rain water stored in the tanks.

Since the Laini Saba community cooker became operational in 2007, Jim Archer has drawn up plans to increase the number of cookers to one per every 50-70 households. He is planning to recycle waste water from bafu closets to flush through the open pit latrines that often block and overflow, which are to be redesigned as "aqua privies". The runoff from the "aqua privies" can then be bio-digested, and the resulting matter and moisture gravity-fed to support the growth of vegetables, fruit trees and shrubs to create green spaces within the slum. This project has attracted wide interest from UN agencies, non-government organisations, as well as private companies

But before that, the temperature of the cooker's firebox must be increased from its current 600 ˚C to 800 ˚C, which is the World Health Organization's minimum temperature requirement for incinerators in the developing world. Jim is confident this can be done easily.

Some 91 250 tonnes of charcoal biomass is used for energy every year in Kenya, Contributing to this are several 'temporary' displaced persons camps, which permanently shelter well over 110 000 people each. Women and children in these camps travel further and further every day to find wood and fuel for cooking, denuding the countryside for miles around and creating health problems for themselves from the smoke of firewood. Recent research findings show that black carbon (BC), the black soot resulting from the incomplete combustion of burning fossil fuels and biomass contributes to warming the planet 55 percent as much as CO_2, and that reducing black carbon emissions may be the quickest, cheapest way to save the climate. Community cookers will contribute a great deal to that.

AIR CONDITIONING & ENERGY FROM DEEP WATER

Deep lake and ocean water and even ground water is being exploited for cooling buildings, providing drinking water, and generating electricity.

The cities of Toronto and Stockholm, and the Cornell University campus have been using cold deep water to cool large buildings and making big savings in energy and carbon emissions and cutting other pollution from energy generating plants.

Toronto, for example, draws cold water from the depths of Lake Ontario to Toronto Island where the water is filtered and treated with chlorine as it is delivered to taps in homes and businesses. After treatment, part of the very cold water flows to a city plant, and via heat exchanger, cools a closed water loop that circulates to the distribution network where more heat exchangers cool the water circulating through the air conditioning systems in the office towers. A total of 46 buildings signed up to the system, saving 85 GWh and reducing 79 000 tonnes CO_2 emission annually.

Honolulu has been investigating the possibility of converting the energy of sun-warmed surface water to electricity (ocean thermal energy conversion, or OTEC). OETC systems include the closed-cycle system that uses a working fluid, such as ammonia, pumped around a closed loop with three components: a pump, turbine and heat exchanger (evaporator and condenser). The warm seawater passes through the evaporator and converts the ammonia liquid into high-pressure ammonia vapour. The high-pressure vapour is then fed into an expander where it drives a turbine connected to a generator. Low-pressure ammonia vapour leaving the turbine is passed through a condenser, where the cold seawater cools the ammonia, returning the ammonia back into a liquid.. The open-cycle system uses the warm seawater as the working fluid. The warm seawater passing through the evaporator is converted to steam, which drives the turbine/generator. After leaving the turbine, the steam is cooled by the cold seawater to form desalinated water. The desalinated water is fit for domestic and commercial use.

The hybrid system uses parts of both open-cycle and closed-cycle systems to produce electricity and desalinated water. In this arrangement, electricity is generated in the closed-cycle system, and the warm and cold seawater discharges are passed through the flash evaporator and condenser of the open-cycle system (i.e., the original open-cycle system with the turbine/generator removed) to produce fresh water. The first OTEC was deployed in Hawaii in 1979.

Japan began pumping up deep ocean water in 1979 to support fisheries that had been depleted by over-grazing of seaweed beds that support fish and marine mammals.

Pumping deep ocean water to air condition cities, produce energy and fresh water, and to fertilize the productive surface waters, appears a promising approach to mitigating global warming by reducing the consumption of polluting oil and coal and the impact of overgrazing on marine food production.

But is large-scale pumping of deep ocean water sustainable? The deep ocean is ventilated through a giant thermohaline circulatory system that moves deep waters from north to south as salt-laden cooled water sinks into the depths in the North Atlantic and energizes a global conveyor belt that sends nutrient laden deep waters naturally to the surface in the North Pacific, north Indian Ocean, and south-east Pacific. This circulatory system is already being seriously disturbed by global warming.

There is a potential threat to deep sea communities as food particles and organisms are sucked up with the cold water and hence removed from the deep water environment. Furthermore, the construction and maintenance of the pump and pipe system could damage the deep sea habitat and its wild life. These applications, if practised on a large scale could contribute to warming the oceans, thereby decreasing their net primary production and impacting on all marine life.

Many big projects have remained on the drawing board also because the technology is expensive. Nevertheless, small scale air conditioning projects are definitely sustainable, and there are increasing examples, including the use of ground water to cool the tunnels of the London underground in the UK, and deep-mine flood water for air-conditioning in Springfield, Nova Scotia in Canada, and Park Hill Missouri in the US.

REEF NOT BARRAGE TO TAP THE TIDES

The Severn estuary has the third highest tidal range in the world, and a barrage across the estuary to trap the high tide could contribute 0.6 percent of UK's primary energy use and 2 percent of its electricity. The barrage, estimated to cost of £15 billion many decades back, had triggered widespread environmental concerns as it would lead to the loss of hundreds of square kilometres of mudflats and salt marsh, home to waders and other coastal birds and a host of migratory species. The powerful surge of water over the turbines when the barrage gates open will profoundly disturb estuarine life, including fisheries and salmon runs.

A possible solution proposed by Cornish hydraulics engineer Rupert Armstrong Evans is to build a reef instead of a barrage that would generate as much electricity and far more steadily than the big barrage. This would consist of a semi-floating set of box structures housing the turbines and stretching across the estuary riding over a fixed base on the estuary floor. By using a moveable 'crest gate' to track the tide level and therefore to maintain a small head difference, irrespective of the stage of the tide, the turbines would operate for long periods, at least double the generation period of the proposed big barrage.

The reef would minimise environmental effects, save on construction and costs and still allow big ships to pass. The UK government announced in 2008 it believes the Severn tidal reef to have merit and would consider it. In July 2009, however, a row broke out as Evans' idea, entered in a Department of Energy and Climate Change competition, was rejected in favour of a similar design put forward by another engineering firm.

SALINE AGRICULTURE TO FEED & FUEL THE WORLD

Shortage of fresh water is a greater threat to world food supply than shortage of fossil fuels, and cultivating salt-tolerant crops could solve both problems.

Fresh water constitutes about 1 percent of water on earth, while another 1 percent is brackish and 98 percent is sea water. Half the global supply of fresh water is now used, and good fresh water is increasingly scarce and expensive. The problem is compounded by salinization from chronic irrigation, making land unsuitable for cultivation, and sea level rise flooding coastal regions that contain a large proportion of agricultural land.

The solution is to cultivate salt-tolerant plants (halophytes) in coastal areas, marshes, inland lakes, desert regions with subterranean brackish aquifers, and directly in oceans or seas. Cultivating halophytes would not compete for land that should be cultivating food, and could provide more food and feed, as well as protection against shoreline erosion and feeding areas for birds, fish and animals. Some halophytes may even reclaim the land for freshwater plants by leaching salt through enhanced percolation, and by storing salt in their leaves that are harvested and removed from the fields.

There are some 10 000 halophytic species of which 250 are potential staple crops. Various livestock can thrive on halophytes or a combination of halophytes and conventional feed. Some are oil-producing plants suitable for edible oils or biodiesel. Micro-algae, in particular are prolific growers. Currently, an Israeli company maintains a 1 000 m^2 site that can produce approximately 23 g dry mass /m^2/day. This translates to more than 5 600 gallons/ha/year of algal oil, compared to palm oil yield at 1 187 gal/ha/y, Brazil ethanol at 1 604 gal/ha/y, and soy oil at 150 gal/ha/y. The theoretical upper limit of micro-algae yield is 100 g dry mass/m^2/day. An area the size of the Sahara desert (13.6 percent of the world's arid and semi-arid area) would be sufficient to produce 16 times the energy used by the world in a year.

HARVESTING SUNLIGHT WITH ARTIFICIAL PHOTOSYNTHESIS

Although we are quite successful in harvesting solar energy with thermal and PV technologies, storing it is a problem. The sun shines intermittently, and then only during the day. So it is necessary to have efficient and cost-effective storage capacity, if solar is to become a primary energy source for society. Nature has solved that problem admirably with photosynthesis. The problem with photosynthesis is that it has not evolved to maximise efficiency in harvesting solar energy because solar energy is rarely limiting; there's usually too much of it and plants have evolved many mechanisms to protect themselves from oxidative damages that strong sunlight can inflict.

There is much scope for artificial photosynthesis to do better in harvesting and storing solar energy. One main approach is photo-electrochemical splitting of water into its elements in an photo-electrochemical cell. This consists of two half-reactions, one reducing water to produce hydrogen, the other oxidizing water to produce oxygen, each of which requires its own catalyst and optimum conditions. Hydrogen can be stored and used as fuel in a fuel cell, which does the reverse of the photo-electrochemical cell: hydrogen is recombined with oxygen to generate electricity.

Much current effort is devoted to finding better catalysts for each of the half reactions in splitting water, but there is also a problem in fitting the two half reactions together.

An efficient and robust catalyst for oxidizing water has been found recently in nano-sized crystal clusters of cobalt oxide, which improves the catalytic activity 1 550 times. Cobalt is also a much more abundant element than the iridium it displaces. The researchers were taking inspiration from nature, which always uses the most abundant materials that can do the job.

Another team of researchers departed from artificial photosynthesis substantially in using a single metallo-organic compound to catalyze the two reactions sequentially and in a cycle that regenerates the catalyst. In the process, they also discovered reactions new to chemistry.

HARVESTING WASTE HEAT

Harvesting heat is particularly fascinating because heat is normally the end of the line as far as energy transformation is concerned. Turning it back into useful energy effectively recycles the waste energy thereby increasing overall energy efficiency. This is another instance of the circular economy of living systems and sustainable systems.

Thermoelectric (TE) devices depend on the thermoelectric effect, the inter-conversion of temperature differences and electricity. A thermoelectric generator creates an electrical voltage when there is a temperature difference on each side. Conversely, when a voltage is applied, it creates a temperature difference. Hence the effect can be used to generate electricity, or as a heat pump to heat or cool objects and spaces. It depends on special TE solid state semiconducting materials.

Miniature TE devices are now in mass production for cooling, heating, and temperature control applications in laser diodes, Polymerase Chain Reaction systems, and portable beverage and picnic coolers. Personal temperature-control systems that provide cooling and heating for the office have come onto the market, as have TE-based cooling systems for computer boards. One main application is power for remote data communication systems for oil and gas pipelines, polar weather station power generators, and cathodic protection for oil drilling platforms. TE generators are chosen for these applications because of their proven reliability (often maintenance-free for 20 years), durability under extreme conditions, and very little if any degradation in performance over their operating life time.

TE generators are being used to harvest waste heat from automobile engine exhaust to boost fuel economy. Further down the line they could provide heating and cooling for vehicles, buses, aircraft, trains, and homes, replacing the refrigerant R-134a that has a greenhouse warming potential 1 430 times that of CO_2. R-134a will be banned in new European cars by 2011; and the US DoE has announced a US$13 million cost-shared programme to develop TE technology for cooling.

CONDENSED MATTER NUCLEAR REACTIONS TRANSMUTATION OF TOXIC NUCLEAR WASTES?

Nuclear fusion is a process whereby the nuclei of light chemical elements fuse together to form heavier ones. As conventionally understood, nuclear fusion only takes place in our sun and other stars, producing all the chemical elements starting from the lightest, hydrogen. A lot of energy is needed to force even t he lightest nuclei to fuse. That is because all nuclei have protons that are positively charged, and as like charges repel, nuclei strongly resist being too close together. However, should they get beyond this 'Coulomb barrier' a strong nuclear attractive force takes over and cause the nuclei to fuse. This is achieved by accelerating the nuclei to very high speeds by heating to 'thermonuclear' temperatures in excess of 10^6 ˚K. Only then would the nuclei get close enough by random collision to fuse together. Once the fusion starts, it generates so much excess heat that it becomes a sustained chain reaction. The hydrogen bomb is an uncontrolled fusion chain reaction.

In 1989, Martin Fleishmann and Stanley Pons claimed that atomic nuclei could be made to fuse at ordinary temperatures with the release of considerable 'excess energy'. They were greeted with derision and disbelief; and 'cold fusion' continued to have a bad press for over a decade.

But a small international coterie of scientists became impressed, especially when Fleishmann and Pons published more substantial results in 1990, documenting the accuracy of their measurements and answering many of the criticisms made against their preliminary findings published the year before. These cold fusion enthusiasts managed to keep the research alive. And at the beginning of 2007, the Royal Society of Chemistry sponsored a symposium. This resulted in a thorough investigation and a write-up by ISIS, which helped bring the subject to the attention of the intelligent public and policy-makers.

Fleishmann and Pons' findings were repeated by many groups, and in many different forms. The key to 'cold fusion' is that it happens in the solid state, or condensed matter state, in which nuclear fusions, plus a whole range of other nuclear reactions can take place much more readily. The cold fusion scientists have pioneered a new discipline of "condensed matter nuclear science", the reactions are often referred to "low energy nuclear reactions" (LENRs).

Fleishmann and Pons packed deuterium (D, or $^{2}H_{1}$, a heavy isotope of hydrogen with twice the atomic mass) into a palladium lattice by electrolysis of heavy water. Palladium has a high affinity for hydrogen, and the palladium electrode absorbed a lot of deuterium. Consequently, the deuterium nuclei (each consisting of a proton and a neutron) are packed in close proximity in the palladium metal lattice, with the help of shielding electron (negative) charges that are also delocalised over the condensed matter. In this configuration, the nuclei can either fuse directly to produce helium-4, $^{4}He_{2}$, or else the proton in the nucleus could capture an electron resulting in two neutrons. These neutrons are special, as they are very slow (ultra-low momentum neutrons) and can easily be captured by other nuclei that undergo beta-decay (ejection of an electron) to give a range of transmutation products.

Electron-capture by proton could also take place in hydrogen nuclei (which have only one proton and no neutron), and that explains why transmutations have been detected in electrolysis of ordinary light water.

The minimum requirement for transmutation is a metal hydride film or membrane loaded up with hydrogen or deuterium to a high level, and kept in constant flux, Electrode materials ranged from carbon, nickel, to uranium. The metal hydride can be loaded by electrolysis of water or heavy water using a thin film of the metal as cathode; or else deuterium gas can be made to diffuse through the metal membrane by injecting the gas on one side and evacuating from the other side. A wide variety of experimental conditions have been used to trigger or speed up the reactions, including surface plasma electrolysis, plasma discharge, laser initiation and external electric or magnetic fields. A typical experiment is run continuously for 260 hours, resulting in a wide variety of elements.

George Miley's team at the University of Illinois Urbana-Champaign in the United States is one of the main groups involved in transmutation. The most commonly reported elements are calcium, copper, zinc and iron, found in more than 20 different experiments. Forty percent of the least frequently observed elements were rare earths from the lanthanide group: lutetium, terbium praseodymium, europium, samarium, gadolinium, dysprosium, holmium, neodymium and ytterbium.

There were other effects associated with nuclear transmutation. These include energetic charged particles, protons (~1.6 MeV) and alpha (~16 MeV) emissions, and low level soft X-ray emissions. Excess heat was also produced simultaneously.

The transmutation of elements is the old alchemist dream come true. The transmutation products fall into five peaks of atomic mass. The maxima and minima in abundances resemble those predicted if ultra-low momentum neutron capture followed by beta-decay were involved in the transmutations in accordance with the theory of Alan Widom at Northeastern University Boston, and Lewis Larsen of Lattice Energy in the United States.

These findings not only challenge the story of how the chemical elements were created, they have the potential for a new source of much safer, cleaner nuclear energy. It could "revolutionize" the energy industry, according to Larsen, in providing highly concentrated energy sources that could, for example, allow a car or an airplane to travel around the world without refuel.

Perhaps more importantly, there is a potential for making safe the accumulated nuclear wastes from conventional nuclear reactors. Spent fuel rod assemblies could be processed on site and injected into co-located LENR transmutation reactors that would 'burn' the hot radioactive wastes down to stable isotopes using large fluxes of ULM neutrons that are easily captured by the radioactive isotopes. This process will also provide an enormous source of concentrated energy for enriching the future zero-carbon world.

RECOMMENDATIONS

1. An explicit national target should be set for 100 per cent green, renewable energy sources by 2050
2. Nuclear power, carbon capture and storage, and large scale biofuel or biochar plantations should be excluded
3. There should be no carbon trading to offset greenhouse gas emissions in developing countries
4. The developed nations must take responsibility for reducing their own emissions at home, while providing genuine financial and technological assistance to developing nations that have to cope with the worst effects of climate change
5. Public investment should be targeted at education, research and development of the appropriate green energy technologies present and future, including those mentioned in this report
6. Grants and subsidies should be targeted to encourage decentralised distributed small scale to micro-generation of green renewable energies, and to promote green initiatives from local communities
7. Feed-in tariffs should be introduced for all new renewable energies
8. Existing nuclear power stations should be decommissioned at the end of their designated life times. Uranium mining should cease and clean-up should begin. At the same time, weapons grade uranium should be consumed in existing reactors in accordance with nuclear disarmament
9. Major public investment should be directed towards making safe toxic and radioactive nuclear wastes by low energy nuclear transmutation

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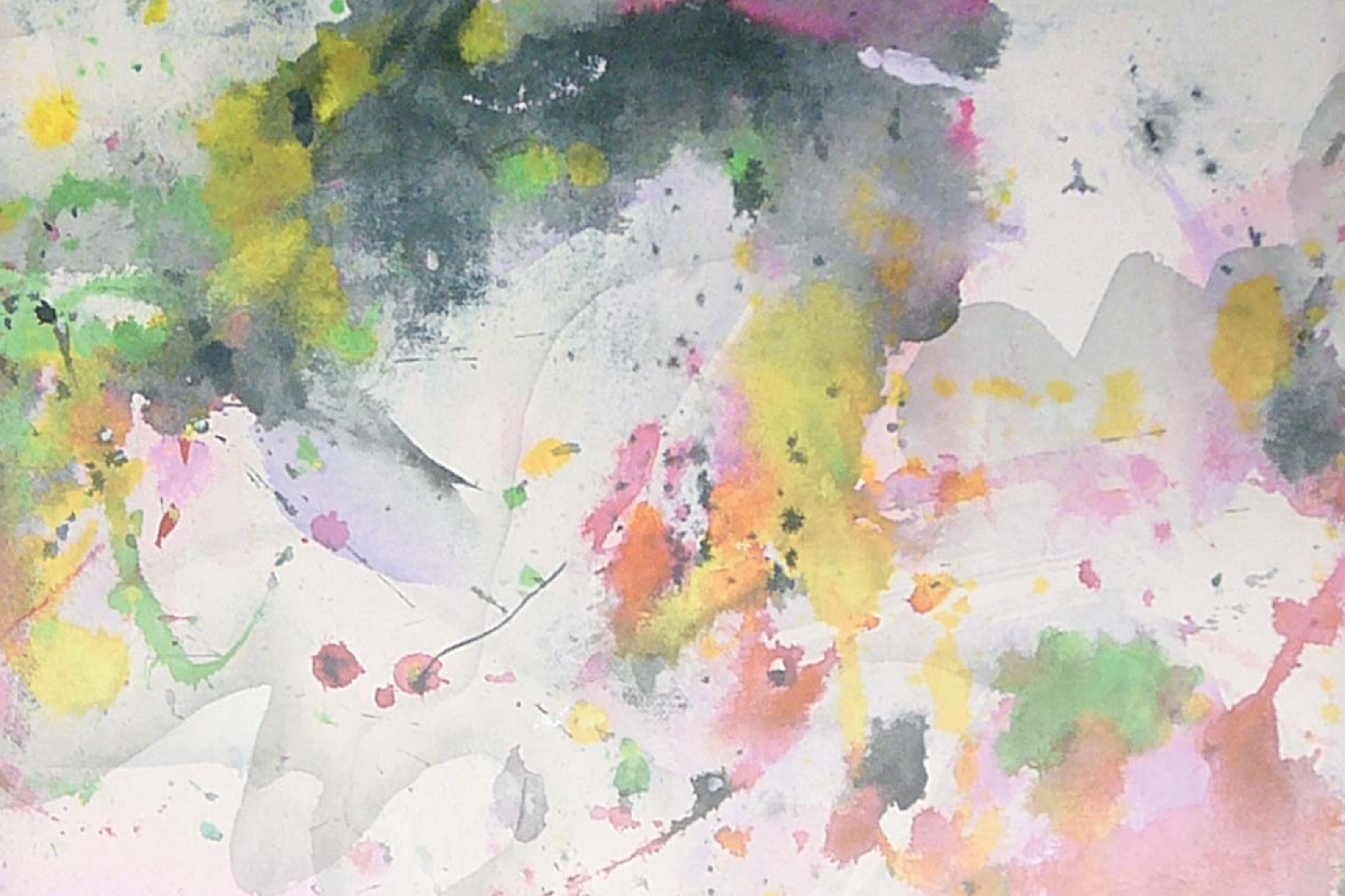


TRANSITION TO LOW CARBON ECONOMY

1

UK'S LACKLUSTER LOW CARBON TRANSITION PLAN

Belated, good in parts, but not green and definitely lacking in vision

Vista 2 by Mae-Wan Ho

THE BELATED

The world is shifting to renewable energies in the wake of peak oil and accelerating global warming. In contrast to exhausting supplies of fossil and nuclear fuels, renewable energy is inexhaustible energy. In 2008, more capacity in renewable energies has been added than conventional, and the trend is continuing, with many politicians and experts considering 100 percent renewable by 2050 a distinct possibility (see Chapter 11). The German government, for one, appears to have made 50 to 100 percent renewable energy by 2050 its target (see Chapter 2).

The UK has lagged far behind. It is trailing the EU league for renewables, being third from bottom, ahead of only Luxembourg and Malta [1]. The UK generated 1 percent of its energy from renewables in 1995; that increased to 1.3 percent ten years later in 2005, and is currently about 1.8 percent.

The UK government's White Paper [2] is a belated attempt to salvage the situation by taking on board the message of the Stern Report [3, 4] including the positive finding that mitigating climate change is not only possible but affordable.

THE GOOD

The short term aim is that by 2020 the UK's emissions should be reduced by 18 percent from the 2008 level, a larger reduction if the Copenhagen summit agrees appropriate international targets. By 2050, emissions are to be cut by 80 per cent from 1990 levels, a target recommended by the Independent Committee on Climate Change as the UK's contribution to halving global emissions by 2050.

A separate report, *The UK Renewable Energy Strategy 2009* [5] from the Department of Energy and Climate Change sets out a path to a "legally binding target" of 15 percent of UK's energy from renewables by 2020, reducing emissions by 750 Mt CO_2 by 2030, and decreasing UK's overall fossil fuel demand by around 10 percent and gas imports by 20-30 percent. A £100 billion new investment will create 500 000 jobs in the renewable energy sector..

The White Paper [2] contains a great deal of detail on how the targets are to be achieved. There is a long list of measures (see Box 1.1) for producing low carbon energy and for reducing energy consumption, and a long appendix giving the savings that each is supposed to contribute. There is to be an EU-wide carbon trading scheme with a total that reduces year by year. There is to be support for energy conservation, for the development of renewable energy sources, for measures to reduce emissions from farms, for the creation of more woodland to remove CO_2 from the atmosphere, and more. That's the good news.

THE BAD

The bad news is that there will be great reliance on carbon capture and storage and on nuclear power; both not renewable, not sustainable and not green (see Chapters 3-7, 9, 10). The Government will seek an agreement on including international air and sea transport into the national emission totals, but there is nothing about taxing aviation fuel, or plans to reduce air travel.

The basic principle underlying the White Paper is "Business as usual, only smarter". We will unplug our old fossil fuel and nuclear power stations from the grid and plug in new, hopefully better ones. We will continue to rely heavily on private transport, though with cars that emit less CO_2 per mile. There will be at least as much air travel in 2050 as today, though in more efficient aircraft. And so on.

Life was very different 50 years ago and it will be very different 50 years from now. It will have to be, if our descendents are to live well and yet produce only a tiny fraction of the greenhouse gases that we do. In a White Paper that claims to look 50 years ahead, there is remarkably little in the way of forward planning to avoid committing our successors to a life style that's essentially the same as ours. Many crucial things like the design of our cities and major infrastructure such as railways take a very long time to change, and if they are to be ready for 2050 the planning has to start now.

Box 1.1
KEY PROPOSALS
All major Government departments have been allocated their own carbon budget and must produce their own plan

- About 30 percent of electricity to come from renewables by 2020
- Up to four demonstration coal burning power plants with carbon capture and storage
- Facilitate the building of new nuclear power stations
- About £3.2 billion to help households become more energy efficient; smart meters in every home.
- People and businesses to be paid for generating electricity from low carbon sources
- Assistance to low income groups
- Support development of green industry including up to £120 million investment in offshore wind and £60 million for marine energy
- A 40 percent cut in average CO_2 emissions from new cars in EU. Support for new electric cars.
- A framework for tackling emissions from farming
- A "smart grid"

About 70 percent of UK emissions come from industrial sectors that are within the EU Emissions Trading Scheme (ETS) and the Government does not propose to limit the number of credits that can be bought to meet the reduction target for this sector

THE WORSE: EMISSION CREDITS

Within the EU, a carbon trading scheme allows some flexibility while the total emissions are being reduced (see Box 1.2). The White Paper, however, anticipates that rather than driving through all the emissions cuts to which it has committed itself, the UK will purchase credits "that will deliver emissions

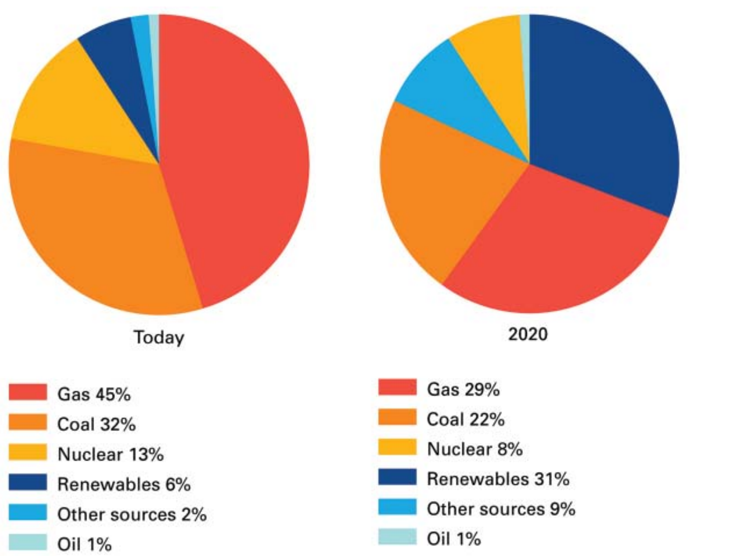


Figure 1.1 UK's planned transition to low carbon electricity generation

Box 1.2
WHAT IS CARBON TRADING?

The principle of carbon trading is that a central body, such as a government or an international organisation, sets a limit, or 'cap', on the total amount of greenhouse gases (GHGs) that can be emitted. Companies buy or are given credits that allow them to emit given amounts of GHGs. If they want to emit more GHGs than they have credits for, they can buy them from companies that intend to emit less than their allowances.

The EU Emissions Trading Scheme (EU ETS) is the largest system of this kind but it will still cover only 45 percent of the EU's emissions. There are a number of criticisms of the EU ETS.

- Countries can offset their carbon emissions by purchasing other countries' unused carbon allowances, resulting in little if any real reduction in total carbon emissions; when offset is done in developing countries as the UK White Paper intends, it effectively places extra burden on developing countries to reduce their emissions [6]
- In the first phase, generators benefited from windfall profits by passing the notional cost of carbon permits onto customers even though they had paid nothing for them. The customers may have to pay again when carbon allowances are no longer free for generators from 2013 [7].
- The EU ETS is concerned only with carbon dioxide and does not include other important GHGs such as methane and nitrous oxide [8].
- The data set used by the EU ETS does not extend back before 2005 with the result that some countries are likely to receive over-allocations of carbon credits [6].
- If carbon trading is to be effective, the price of carbon needs to be at a level that encourages countries to reduce emissions while also promoting new technology. In general, carbon trading schemes advantage old companies over new entrants, yet it is the latter that are more likely to be employing low carbon technology [4].

reductions in developing economies." In other words, the UK will reduce its carbon emissions by less than it has agreed to and the developing countries will reduce theirs by more.

The effect could be very large indeed. About 70 percent of UK emissions come from industrial sectors that are within the EU Emissions Trading Scheme (ETS) and the Government does not propose to limit the number of credits that can be bought to meet the reduction target for this sector. Only that can explain why the Government can issue a White Paper detailing the swingeing cuts in emissions that are going to be required and at the same time give the go-ahead for a third runway at Heathrow and at least four new coal-fired power stations without CCS [9].

If we go ahead with nuclear power, our children and grandchildren are likely to find themselves picking up a bill for waste disposal that will make our £73 billion look pretty small beer. They will be burdened with toxic and radioactive wastes of mammoth proportions including those we haven't been able to deal with

CARBON CAPTURE & STORAGE

At present, about 45 percent of our electricity is generated from gas and about 32 percent from coal. (See Fig. 1.1). The White paper estimates that in 2020, those figures will still be 29 percent and 22 percent respectively. The Government is placing great reliance on carbon capture and storage (CCS) in which the carbon dioxide produced in burning fossil fuels is captured and transported to an underground repository such as a depleted oil field. As the White Paper itself admits, this has never been tried on a commercial scale, and while the three stages have each been shown to work, the process as a whole has not [10] (see Chapter 9).

The new Department of Energy and Climate Change is to support up to four demonstration plants, and as other countries are going to build them as well, the Government is confident that a way will be found to make CCS safe and economical on the scale required. If not, it is hard to see how the targets will be met, because there is no plan B.

If CCS does work, there will be increased worldwide demand for fossil fuels; thereby hastening the arrival of peak gas and coal in addition to oil, especially because the CCS system is estimated to use up between 10 and 40 per cent of the energy produced by the plants to which it is fitted [10].

NUCLEAR ENERGY

At present, about 13 per cent of our electricity comes from nuclear. This will be reduced to 8 per cent by 2020 because old stations will be decommissioned faster than new ones can be built; the proportion is intended to rise again after 2020 but there is no target figure.

One of the strongest arguments against nuclear power is that it is not economical. The nuclear industry has been notorious for cost overruns during construction of power plants. But that is nothing compared to the downstream costs of decommissioning and waste management and disposal [11, 12]. When the Thatcher government privatised the electricity generating industry in 1989, they were unable to sell off the nuclear power stations because they were not seen as good investments. The taxpayer had to take over all the liabilities and the costs of running the dirtiest, loss-making parts of the industry at Sellafield, now £3 billion a year and rising. Meanwhile the cost of clean-up and decommissioning has ballooned to over £73 billion. Sellafield has become the world's nuclear waste dump with no end in sight, its waste

Box 1.3

CHILDHOOD CANCERS LINKED TO NUCLEAR POWER STATIONS

For years there have been conflicting reports about whether the incidence of childhood cancers, especially leukaemia, is higher in the vicinity of nuclear power stations. As the numbers are small it can be difficult to decide whether an observed cluster represents a real effect or merely due to chance [16].

Now research commissioned by the German Bundesamt für Strahlenschutz (BfS, Federal Office for Radiation Protection) [17, 18] found a significantly increased incidence of leukaemia in children living within 5 km of a nuclear power plant, and a smaller but still significant increase in children living between 5 km and 10 km. They also found a statistically significant regression coefficient between the increased incidence of leukaemia and distance from the power station; this correlation is more compelling evidence than the existence of clusters. Their conclusions have been confirmed in a recent detailed analysis [19]

But the UK Government dismissed this evidence in its White Paper [2] on the grounds that the correlation does not prove that ionising radiation emitted by German nuclear power stations was the cause of the leukaemia. It also stressed that the report of the UK Committee on Medical Aspects of Radiation in the Environment (COMARE), which found no link, was based on a considerably larger number of cases, but did not mention that the BfS report was based on a "case-control" study in which each information such as the distance from the home to the power station was known exactly for each child in the study [20].

In fact, while COMARE found no greater incidence of cancer near nuclear power stations, it did find a greater incidence near the nuclear installations at Sellafield, Aldermaston, and Rosyth.

The UK Government is applying as usual the *anti*-precautionary principle with regard to childhood cancer and nuclear power stations. This is much the same argument that the tobacco industry used: just because the incidence of lung cancer is higher in smokers and correlated with the number of cigarettes smoked, that does not prove smoking causes lung cancer and there is no need to stop manufacturing and marketing cigarettes.

reprocessing plants non-functional, and there is as yet no designated final waste repository.

According to the White Paper, "it will be for energy companies to fund, develop and build new nuclear power stations in the UK, including the full costs of decommissioning and their full share of waste management and disposal costs." That means the Government will build a facility to dispose of the waste from existing plants and the industry will be expected to pay only the extra cost of adding waste from the new ones. The Government has not yet decided how to estimate those costs but it seems likely that the companies will pay a risk premium in return for which there will be an upper limit to what they will be required to contribute. Anything above that limit will be again for the taxpayer to cover.

If we go ahead with nuclear power, our children and grandchildren are likely to find themselves picking up a bill for waste disposal that will make our £73 billion look pretty small beer. They will be burdened with toxic and radioactive wastes of mammoth proportions including those we haven't been able to deal with.

Safety is decidedly a major issue with nuclear power [13] (see Chapter 4). It turns out that no nuclear power plant, not even the 'generation 3' reactors under construction are proof against malfunction or malevolent attacks. In addition, a main source of hazard is spent fuel stored on site in overcrowded cooling ponds before they are shipped out for storage in the final repository. These can easily catch fire and cause explosions. Sellafield has been declared "the most hazardous place in Europe" by its deputy managing director [14], and a "slow motion Chernobyl" by Greenpeace.

The fallout from Chernobyl was 30 to 40 times that released by the atom bombs of Hiroshima and Nagasaki in Japan during World War II. A 2005 report attributed to Chernobyl 56 direct deaths and an estimated 4 000 extra cancer cases among the approximately 600 000 most highly exposed, and 5 000 among the 6 million living nearby [15].

There is also strong new evidence from Germany linking childhood leukemia and proximity to nuclear power stations, This gives a hint on the health burdens of accumulating toxic and radioactive wastes from the nuclear industry to present and future generations.

But the White Paper persists in dismissing such evidence, as the UK Government has been doing for years (see Box 1.3).

RENEWABLES

In principle, the White Paper [2] is encouraging about the future of renewable energy, and the detailed strategy laid out in a separate report [5]. The Government says it will encourage wind power, both onshore and offshore; it will retain the Renewables Obligation and Climate Change levy to encourage investment in renewables, and make it easier to connect to the grid. Feed-in tariffs for renewables will be introduced [5]. It will investigate the possibility of power from the Severn Estuary; it will support anaerobic digestion, and so on. But there is certainly nothing like the enthusiasm expressed by the German Federal Ministry of Economics and Technology, which sees renewables as a major industry in Germany and boasts that "Renewables made in Germany" are already highly successful in world markets [21].

TRANSPORT

Domestic transport is responsible for about a fifth of the UK's emissions, and the White Paper proposes many measures for reducing this contribution, from electric cars to improving the tyres on heavy goods vehicles. There is a lot on making cars more carbon efficient and some on incentives to move from car to rail or bus or even bicycle. But there is nothing about redesigning our cities to make a car less of a necessity.

It is not easy to make this sort of change, but the White Paper is about the period up to 2020 and looks ahead to 2050. This gives the government the opportunity to introduce long term policies that will make it possible to move away from dependence on car ownership without detracting from the quality of life.

Another disappointing feature is that the government assumes there will be even more air travel in 2050 than today. While there are plans to move traffic from road to rail, the Government seems to have little interest in discouraging air travel. On the contrary, it reiterates the importance of expanding the capacity of Heathrow. Shortly after the White Paper was published, however, plans were announced for a high speed rail service connecting London and Glasgow. We have not heard the last of this debate.

LAND & WASTE

Farming, forestry and land management are responsible for about 7 per cent of UK greenhouse gas emissions; and the release of methane from decomposing waste accounts for a further 4 percent

Most of the emissions from farms come either from animals or from fertiliser, and farmers will be shown how to reduce these. The Government does not, however, mean to take this as far as giving additional support to organic farming. This is most disappointing in view of the enormous potential that organic agriculture and localised food and energy systems have for saving energy and mitigating climate change, as documented in our report [22] *Food Futures Now: *Organic *Sustainable *Fossil Fuel Free*, and updated since [23].

THE INTERNATIONAL ASPECT

Climate change is a global problem and needs global solutions. Up to a point, the government is conscious of this. It recognises, for example, the need to have globally agreed targets for the reduction of CO_2 emissions and an agreement on how to include international air and sea transport in the total.

But a document that looks forward to 2050 should be thinking more about what the world will be like by then. We will have reached the end of the era in which the relatively few of us in the North have a life style very different from the rest. You only have to visit China or India or many other developing countries to see this change happening. By 2050, what is now the third world will have caught up economically and will be able to pay for oil, coal, gas and even uranium at the same rate that we do, and emit CO_2 at the same per capita rate. Buying emissions credits from developing countries is immoral; there will soon come a time when we also won't be able to afford it.

Buying emissions credits from developing countries is immoral; there will soon come a time when we also won't be able to afford it

CONCLUSION

Parts of the White Paper are, as the curate said, excellent. It makes the case that climate change is real and it commits the UK government to doing something about it. The plan is detailed enough that every sector knows what is expected of it; no one is going to be able to do nothing on the grounds that their contribution to the total is too small to matter.

There are, however, important shortcomings; notably the heavy reliance on nuclear energy, the hazards and the problems surrounding waste disposal very much played down; and carbon capture and storage that has never been properly tested either for safety or for economic viability.

Most of all, the White Paper is remarkably unimaginative in envisaging a UK in 2050 very little different from today: still relying heavily on fossil fuels, still travelling by air and in private cars, still taking it for granted that as a wealthy country it has first call on the world's non-renewable resources and will be able to buy all the emissions credits it needs, leaving the real reductions to be made by others.

Recent events are making the White Paper obsolete almost before the ink is dry. In the USA, the nuclear power industry has so far failed in its efforts to overturn any ban on building more reactors, and the Obama administration had put a freeze on Yucca Mountain as long-term waste disposal site. Even Canada, which has its own supplies of uranium and its own design of reactor, the CANDU, has put its programme on hold (see Chapter 3). The UK Committee on Climate Change told the Government that if air travel is not curbed, the rest of the economy will have to cut emissions by 90 percent rather than the currently expected 80 percent [24]. What's more, the Chair of the Intergovernmental Panel on Climate Change is advising that rather than allow the greenhouse gas level in the atmosphere, currently 385 ppm, to stabilise at 450 ppm, we must reduce it to 350 ppm if we are to avoid irreversible climate catastrophe [25].

The Government will have to think again, and be both bolder and wiser.

2

GERMANY
100 PERCENT RENEWABLES BY 2050

Sets an example for all industrial nations

Vista by Mae-Wan Ho

The UK's Low Carbon Transition Plan (Chapter 1) falls well short of the challenges that face us. Fortunately, we need look no further than across the North Sea to Germany for inspiration. Germany is a large, prosperous, industrialised country rather like the UK in many ways. It has traditionally relied heavily on coal for electricity generation, and has a number of nuclear power plants. But there the similarities end.

RENEWABLE ENERGY EXCLUDES NUCLEAR

While the UK's White Paper envisages the Great Britain of 2020 or 2050 as much the same as today, Germany is looking forward to a quite different future in which Germany will guarantee itself a secure energy supply and maintain its position as a world leader in new technology. It is forging ahead in the development and use of renewable energy; and nuclear power - seen in the UK as a major component of the future energy mix - is being phased out altogether.

The nearest equivalent in Germany to the British White Paper is a document issued by the German government in January 2009, with the title *New Thinking – New Energy. Ten Guiding Principles for a Sustainable Energy Supply* [1].

The document sets out the following objectives:

- By 2020, greenhouse gas emissions are to be reduced by 40 per cent from their 1990 levels – double the UK target. (By the end of 2007 emissions had already been reduced by 21.3 per cent.)
- Energy productivity should be increased by 3 per cent every year, so that in 2020 energy will be used twice as efficiently as in 1990
- The proportion of energy that comes from renewables should be increased. By 2050, half of primary energy consumption should come from renewable sources. By 2020, the proportions of final energy consumption, gross electricity consumption and energy used for heating that come from renewables should be double their current levels (which are 9 per cent, 15 per cent and 7 per cent, respectively).
- By 2020, a quarter of energy production should come from combined heat and power generation (CHP), again double the present level.
- The use of biofuels should be increased so that by 2020, 7 per cent of the greenhouse gas emissions due to fossil fuels are eliminated.

100 PERCENT RENEWABLES BY 2050

But speaking to the press [2] David Wortmann, Director of Renewable Energy and Resources at Germany Trade and Invest, a government body supporting the country's renewable energy sector, expressed the view that Germany could be 100 percent renewables-powered by 2050. "It's ambitious, but Germany can be running on renewable energy by 2050 if there is the political will," he said.

In 2008, Germany's primary energy consumed was 7.3 percent renewable, and that figure is predicted to increase to 33 percent by 2020. At that rate of increase, it could well be 100 percent renewable by 2050.

Part of what makes that possible is to use less energy by increasing energy efficiency. The Roadmap lays out a raft of new energy efficiency measures including the construction of a smart grid that should reduce consumption by 28 percent in the next two decades: from 13 842 PJ in 2007 to 12 000 PJ in 2020 and 10 000 PJ in 2030. This will mean enormous savings on costly energy imports.

Another strategy is to make full use of German's natural wind resources concentrated along the northern coastlines, where huge offshore wind parks in the North Sea could generate as much as 10 GW or more (see later), feeding electricity into a smart national grid connecting the north and east of the country and south and west with optimal efficiency using high voltage direct current.

Solar energy will be imported via Italy from the solar thermal plants to be built in the sun soaked deserts of North Africa (but see Chapter 12).

Electric powered cars rechargeable from renewable energy sources will be racing down Germany's Autobahns and cut greenhouse emissions substantially.

"The technical capacity is available for the country to switch over to green energy, so it is a question of political will and the right regulatory framework," Wortman said. Germany plans to use all the renewable energy sources at its disposal, wind, solar, geothermal, hydropower and biomass in an optimum mix.

Wortman praised the government for its plans to invest more into research. "Germany has been a centre of innovation in renewable energy technologies for years. There is a real desire to see it continue to be a place where new central renewable energy technologies are development. Not only the government, but also companies are focussing more resources on research." Wortman said.

He predicted that bio-energy will play a key role, but only where it is sustainable and did not compete with food crops or supplies. In 2008, biomass supplied 3.7 percent of the electricity in Germany, up from 3.1 percent in 2007; while wind power's share increased by 0.1 percent from 6.4 to 6.5 percent.

He singled out a biogas electricity plant developed by Dr. Michael Stelter of the Fraunhofer Institute for Ceramic Technologies and Systems in Dresden that uses compost and waste. A new procedure that uses enzymes to break down cellulose in compost waste means that the plant produces 30 percent more biogas and does this in 30 days, rather than the current 80 days.

To optimize efficiency, the biogas is pumped into fuel cells that operate at 850˚C, allowing the plant to convert biogas methane to electricity at 40 to 55 percent efficiency. Taking into account the heat produced, the fuel cell has a conversion rate of 85 percent.

STRONG GOVERNMENT SUPPORT FOR RENEWABLES

Germany has stolen a march on other member states of the European Union and most of the rest of the world in launching its low carbon transition in earnest more than a decade ago. Germany's renewable energy policy really began in 1974 after the first oil crisis, and consisted almost exclusively in promoting research for the first 15 years [3]. Market creation measures only came after 1988; of these the most important was the Feed-in Law. From 1991 to 1995, under the 1 000 roof programme, applicants received 50 percent of investment costs from the federal government plus 20 percent from the land governments. Eventually 2 250 roofs were equipped with photovoltaic (PV) modules, producing a total of about 5 MW.

For wind energy, the government introduced a programme for subsidising 100 MW – later 250 MW – by a payment of €0.04/kWh (later reduced to €0.03). This was accompanied by the Feed-in Law, that obliges national electricity utilities to buy electricity generated from renewable sources at above-market rates set by the government. As a result, newly installed wind capacity shot up from about 20 MW in 1989 to over 1 100 MW in 1995.

In subsequent years, these subsidies declined rapidly, and the Feed-in Law barely survived attacks from the conventional electricity generators.

Significant improvement came after the 1998 election, when the ‘red-green’ coalition came into office, and strengthened renewable energy support, especially for PV and biomass, thanks also to activists and municipal utilities. Eurosolar’s 100 000 roof proposal since 1996 and the German Solar Energy Industries Association, played key roles in the continued growth of the PV market after the 1 000 roof programme.

The new federal government emphasized ecological modernisation and climate change policy as well as job creation and socio-economic development. It included eco-tax on energy, phasing out nuclear power and strengthening renewable energy sources and combined heat and power generation for increased efficiency of energy use.

The government’s measures to promote renewable energy included a five-year market incentive programme that provided about € 445 million from 1999 to 2002; a tax break on bio-fuels in keeping with a EU directive; and most importantly, it adopted the 100,000 roof programme for PV, and the Renewable Energy Sources Act adopted in 2000 and substantially amended in 2004. This new Law repealed the Feed-in Law of 1990 but maintained an essential feature, i.e., the reliance on feed-in tariffs to encourage the development of renewable energy sources for electricity. This has given German PV and other renewable technologies a further boost. In 2006, Germany accounted for 56 per cent of the world’s solar energy technology market and around 80 per cent of the European market [4].

Germany already generates 6.5 percent of its electricity from wind [2] and is planning to increase this amount. In September 2009, the cabinet announced plans for up to 40 offshore wind parks holding as many as 2 500 turbines and projected to generate 12 GW by 2030 [5]

There are also plans for other sources including biogas, small hydroelectric plants and geothermal. In July 2009, a large group of German companies announced a joint investment of €400 billion ($560 billion) in concentrated solar power (CSP) plants in the Sahara Desert. These are seen as making significant contributions to the total energy supply but are also important because the energy supply is predictable or storable and can provide a buffer against fluctuations in other sources (but see Chapter 12 for strong reservations on big CSP projects).

NO NUCLEAR & NO CCS FOR 2020

Unlike the UK government, the Germans are confident that they can achieve their aims without nuclear power. In 2002 they decided to phase out their nuclear plants by 2022, and while the present Chancellor, Angela Merkel, is known to favour extending the stations’ lifetimes beyond that date, there is little support for building any new reactors. Public opinion in Germany is against nuclear energy especially after the July 2009 incident in which the Krümmel nuclear reactor had to be shut down for the second time in two years and the revelation of problems at the Gorleben site which is intended for long term storage of nuclear waste [6].

Germany, in sharp contrast to the UK, is looking forward to a future in which more and more, if not all of its energy comes from renewable sources. It clearly sees this as an opportunity: the creation of 500 000 new jobs and establishing Germany as a major exporter of renewable technologies; and substantially reducing energy imports

Germany has traditionally relied very heavily on coal and so like the UK, is actively pursuing research into CCS. Vattenfall, a Swedish-German firm, has applied for EU funding to help it build a 385 MW demonstration plant [7]. Germany is not, however, depending on CCS to help it achieve its emissions targets in the same way that the UK is. In particular, it is not included in their plan for reaching their 2020 target because they do expect it to be commercially available by then. Instead, while they will still be generating 40 per cent of their electricity from coal, the emissions will be reduced by increasing the efficiency of the plants, by having more combined heat and power CHP installations, and by an 11 per cent reduction in total energy consumption. If CCS proves successful, they will be well placed to take advantage of it; if it does not, they have other strings to their bow.

Germany, in sharp contrast to the UK, is looking forward to a future in which more and more, if not all of its energy comes from renewable sources. It clearly sees this as an opportunity: the creation of 500 000 new jobs and establishing Germany as a major exporter of renewable technologies; and substantially reducing energy imports

TRANSPORT & TAX ON AIRLINES

Like the UK, Germany is looking at specific measures to reduce carbon emissions from the transport sector, such as improving the efficiency of vehicles and moving traffic from road to rail and from private cars to public transport. But the Germans start with the advantage of a superior rail network. Unlike their British counterparts, the German Federal Department for the Environment is advocating that airlines pay tax on aviation fuel and VAT on tickets for international flights, thus removing a major subsidy to the industry [8].

NO CARBON TRADING

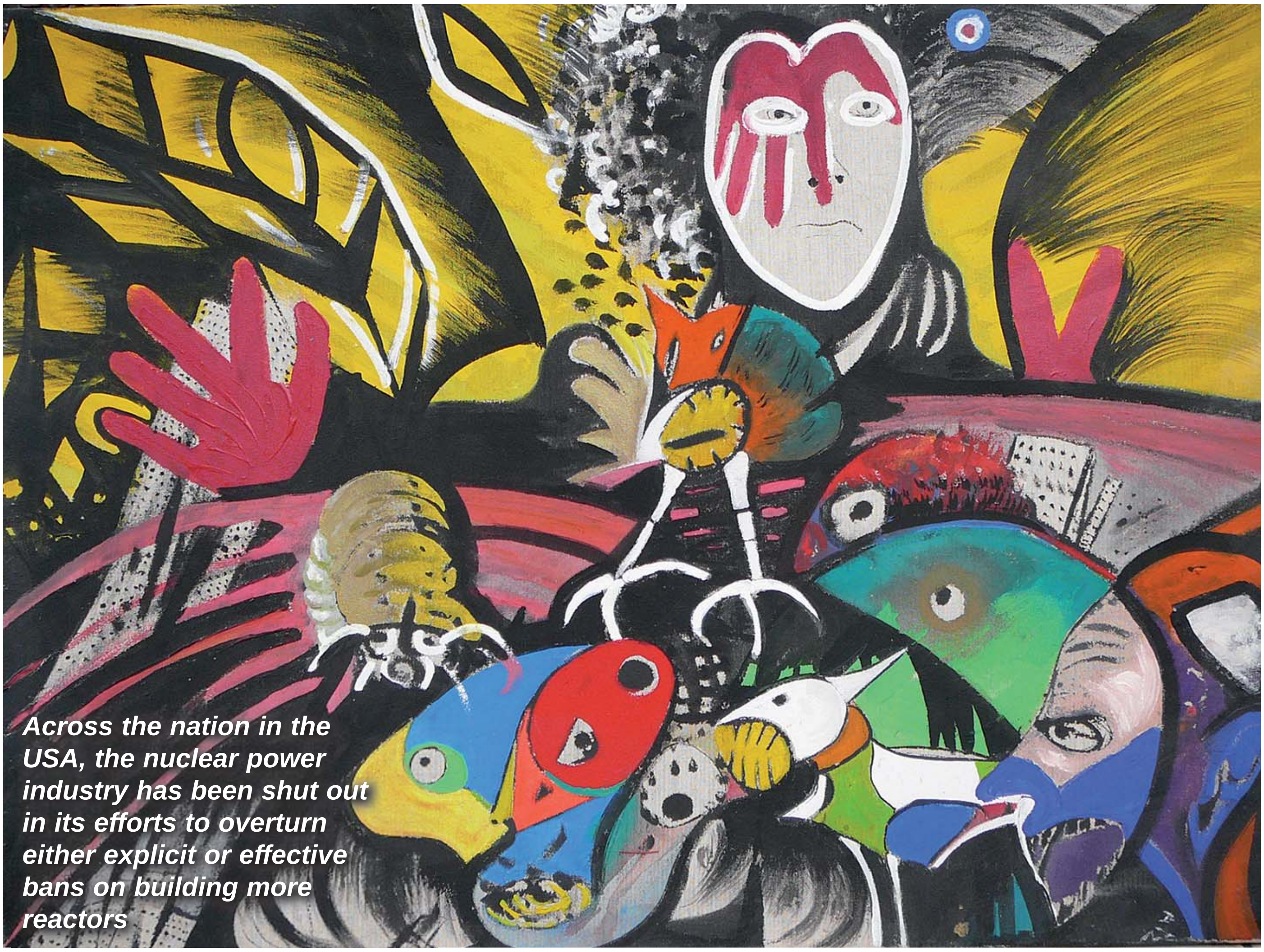
While the UK White Paper assumes that carbon trading will make an important contribution to meeting the country’s emissions target, the UBA explicitly states that Germany aims to reduce its greenhouse gas emissions by measures implemented within Germany itself.


HOW NOT TO BE GREEN

3

NUCLEAR RENAISSANCE UNRAVELS

New nuclear programmes suffer major setbacks



Across the nation in the USA, the nuclear power industry has been shut out in its efforts to overturn either explicit or effective bans on building more reactors

Across the nation in the USA, the nuclear power industry has been shut out in its efforts to overturn either explicit or effective bans on building more reactors, to usher in the much touted "nuclear renaissance" as a way our of the climate crisis [1]. So far, it has been defeated in Arizona, California, Kentucky, Minnesota, Missouri, Hawaii, West Virginia and Illinois.

Michael Mariotte, executive director of Nuclear Information and Resource Service (NIRS) predicts a tougher year ahead for state lobbyists of the nuclear industry on account of two developments. The Obama administration had put a freeze on Yucca Mountain as long-term waste disposal site in February 2009, with both Obama and Energy Secretary Steven Chu reported stating emphatically that "nuclear waste storage at Yucca Mountain is not an option, period" [2]; and new evidence of runaway construction costs: an estimated $6 billion to $12 billion for one reactor [1].

The NIRS was founded 31 years ago to be the national information and networking centre for citizens and environmental activists concerned about nuclear power plants as a means of addressing the climate crisis.

Canada, another enthusiast for the nuclear renaissance has also put its nuclear upgrade plans on ice in July 2009, two years into the $20 billion project to replace aging reactors with 'next generation' technology [3]. The provincial government of Ontario cited excessive costs and uncertainties involving the ownership status of the sole Canadian bidder.

WORLD SIGN UP TO "NUCLEAR RENAISSANCE"

At the (G8) summit in Hokkaido, Japan, in early July 2008 world leaders had reiterated their commitment to build new nuclear power stations. They saw a "nuclear renaissance" in mitigating climate change and energy security that would reduce dependence on fossils fuels and greenhouse gas emissions [4, 5]. The G8 includes the industrial nations Canada, France, Germany, Italy, Japan, Russia, United Kingdom and the United States of America. The European Union is represented but does not have the right to host or chair a meeting. Also invited to the summit were China and India.

Some 29 countries worldwide had indicated they wish to introduce nuclear power, while most existing users have announced plans to expand their nuclear capacity. By 2030, Japan would increase nuclear power generation to as much as 40 percent of total electricity, and Russia's share of nuclear power would grow to 20-25 percent from the current 16 percent [6].

UK Prime Minister Gordon Brown announced that Britain must build "at least" eight new nuclear power stations during the next 15 years to replace ageing plants and contribute to a "post-oil economy" [7]. Italy's then newly elected government said that within five years, it planned to resume building nuclear plants [8]. The country dropped nuclear energy 20 years ago after a referendum resoundingly condemned nuclear power.

France has been the world's top nuclear nation, and will continue in that capacity Germany and Belgium had stood alone among nations that use nuclear power, but have long prohibited the building of new reactors, although old ones are allowed to continue operating for their natural lifespan. For Germany, the end of nuclear power will be 2022 (see Chapter 2)

Across the Atlantic in Canada, the nuclear industry showcased its technology and expertise to more than 100 delegates representing 35 countries at the World Nuclear University (WNU) for a six-week series of lectures, facility tours and special events during July and August 2008 [9]. The WNU was inaugurated in 2003 in London, UK, as a "global partnership committed to enhancing international education and leadership in the peaceful applications of nuclear science and technology."

Back in the summer of 2006, Canada's Prime Minister Stephen Harper, in a key speech to the UK Chamber of Commerce, noted that Britain is among those countries poised to begin buying new reactors for the first time in decades, and said [10]. "We'll hope you remember that Canada is not just a source of uranium, we also manufacture state-of-the-art CANDU reactor technology, and we're world leaders in safe management of fuel waste." That last claim turns out to be gross overstatement [11] see next chapter).

There has been a well-orchestrated effort worldwide to promote nuclear power. One of the instruments is the World Nuclear Association (WNA) [12], formerly the Uranium Institute, a

The Obama administration had put a freeze on Yucca Mountain as long-term waste disposal site in February 2009, with both Obama and Energy Secretary Steven Chu reported stating emphatically that "nuclear waste storage at Yucca Mountain is not an option, period"

confederation of companies connected with nuclear power production from uranium mining to electricity generation and is responsible for 95 percent of the world's nuclear power outside the US. According to the WNA [13] (accessed in September 2008), China plans a five-fold increase in nuclear capacity to 40 GW by 2020, while India's target is to add 20 to 30 new reactors by 2020; Russia plans to build 40 GW of new nuclear power by 2025; Finland and Sweden have designated permanent disposal sites for nuclear wastes that are accepted by local communities; and several countries in Eastern Europe are currently building (Romania) or have firm plans to build new nuclear power plants (Bulgaria, Czech Republic, Romania, Slovakia, Slovenia and Turkey)..

In late December 2007, Warren Buffett, "whose name is synonymous with sound money" turned his back on nuclear power

US NUCLEAR FUTURE UNRAVELS

In the US, the push for nuclear power began in 2002, when George W. Bush launched the Nuclear Power 2010 programme for the construction of at least three major nuclear power plants [14]. The US Energy Policy Act of 2005 then offered three major forms of subsidy. New nuclear power plants could get production tax credits, federal loan guarantees and construction insurance against cost overruns and delays, together worth $18.5 billion.

Christian Parenti, writing in The Nation [14] revealed how the Nuclear Energy Institute, industry's main trade group, hired the PR firm Hill and Knowlton to run a slick campaign to green wash nuclear energy. Part of their strategy involves an advocacy group with the grassroots-sounding name, Clean and Safe Energy Coalition. At the hub of the campaign are former Environment Protection Agency chief Christine Todd Whitman and former Greenpeace co-founder turned "corporate shill" Patrick Moore (also a champion of GM crops). Ghost-written op-eds are placed under the bylines of "scientists for hire".

All the major environmental groups in the US oppose nuclear power. But the PR campaign is having some impact. The online environmental journal Grist found that 54 percent of its readers are ready to give atomic energy a second chance; and 59 percent of Treehugger.com readers feel the same way.

But despite all the corporate spin, public subsidies and presidential speeches, there were already signs that the nuclear rebirth was coming to a halt.

In late December 2007, Warren Buffett, "whose name is synonymous with sound money" turned his back on nuclear power. His MidAmerican Nuclear Energy Company scrapped plans to build a plant in Payette, Idaho, because no matter how many times the managers ran the numbers, and they have already spent $13 million doing so, they found they could not balance the books. South Carolina Electric and Gas too, has suspended its two planned reactors, citing costs as the key factor. If nuclear power breaks ground soon, it will likely be NRG Energy's double-reactor plant to be built in South Texas. But that one has also been delayed.

According to Arjun Makhijani of the Institute for Energy and Environment Research [14], "Wall Street doesn't like nuclear power." Parenti agrees, "nuclear power is too expensive and risky to attract the necessary commercial investors." He points out that even with vast government subsidies it is difficult or almost impossible to get proper financing and insurance. The massive federal subsidies on offer will cover up to 80 percent of the construction costs of several nuclear power plants in addition to generous production tax credits, as well as risk insurance. The average two-reactor nuclear power plant is estimated to cost $10 billion to $18 billion to build. That's before cost overruns, and "no US nuclear power plant has ever been delivered on time or on budget."

Parenti remarked [14] "Rarely has so much money, scientific know-how and raw state power been marshalled to achieve so little." An investment of several hundred billion dollars resulted in a US nuclear industry of 104 operating plants, about a quarter of the global total that produces just 19 percent of electricity in the country.

"Atomic optimism run amok caused the largest municipal bond default in US history," Parenti recalls. In 1983, Washington Public Power Supply System abandoned three nuclear plants in mid-construction, plagued by massive cost overruns and incompetent contractors. When the project finally died, unfinished costs had ballooned to $24 billion, and the utility abandoned $2.25 billion worth of bonds.

In 1985 Forbes called the nuclear industry "the largest managerial disaster in history."

"Rarely has so much money, scientific know-how and raw state power been marshalled to achieve so little." An investment of several hundred billion dollars resulted in a US nuclear industry of 104 operating plants, about a quarter of the global total that produces just 19 percent of electricity in the country

FRANCE PEDDLES NUCLEAR SAFETY IN SHREDS

France remains the world leader and largest net exporter of electricity from nuclear power, gaining €3 billion a year. It is building its first 'generation 3' reactor – the European Pressurized Reactor - at the Flamanville Nuclear Power Plant site, and planning a second [15]. Nuclear power has dominated France since the early 1980s. The country's main electricity company EDF (Électricité de France) manages its 59 nuclear power stations which generate 78 percent of its electricity. Much of France's electricity (18 percent) is exported, to Belgium, Germany, Italy, Spain, Switzerland and the UK. France has long enjoyed a reputation as Europe's nuclear energy expert, and is fully committed to continue in that role. In 2005, EDF announced plans to replace the current nuclear plants with new 1.6 GWe units as they reach the end of their licensed life starting around 2020. France's nuclear company Areva has a pilot EPR plant under construction in Finland (already plagued by delay and cost overrun [16] (see Chapter 5), and marketing activities have been extended to the US and China.

Areva made €743 million in profits in 2007. Areva has long benefited from the low priced uranium ore from Niger, a former French colony in West Africa. It also runs uranium mines in Canada, and has operations at 40 locations in the US.

Sarkozy made selling nuclear power infrastructure an important element of his visits abroad. On 11 July, Areva was declared the preferred bidder for the Sellafield site in the UK that is supposed to generate €1.6 billion annually. A nuclear energy deal was part of the €10 billion trade package negotiated between Sarkozy and Libyan dictator Muammar Gaddafi in December 2007. Sarkozy negotiated a €8 billion sale of nuclear plants to China in November 2007, and Areva obtained a €1 billion uranium enrichment contract in South Korea in June 2007.

But in the very week that the G8 and other leaders were pledging their nations to the nuclear renaissance, a series of nuclear accidents was sending shock waves throughout France, severely denting the façade of competence and safety in the use of nuclear energy that the country had created around itself.

4

SPOTLIGHT ON NUCLEAR SAFETY

Safety seriously amiss and no protection against sabotage

A fire in the spent fuel pool at a reactor like Vermont Yankee in Pennsylvania, USA, would cause 25 000 fatalities over a distance of 500 miles if evacuation were 95 percent effective

Copenhagen street painting 1

ACCIDENTS IN TOP NUCLEAR NATION

In the first week of the July 2008 G8 summit, and as Sakozy assumed the role of president of the EU, the Tricastin nuclear power station in southern France malfunctioned, resulting in 30 000 litres of a solution containing 12 percent enriched uranium to overflow from a reservoir into the nearby Faffiere and Lauzon rivers, raising the concentration of uranium in the two rivers 1 000-fold [1]. This was the first of a series of 9 blunders and leaks in France's nuclear reactors in three weeks since 7 July [2]. After initially downplaying the seriousness of the accidents, the French government was goaded into action. The Environment Minister Jean-Louis Barloo acknowledged that France's nuclear facilities experienced a total of 115 "small irregularities" in 2008. Borloo said the government would need a comprehensive examination of France's atomic industry

The non-government organization CRIIRAD (Independent Commission of Research and Information on Radioactivity) had already noted many malfunctions on the Tricastin site [3]. High radiation levels had been measured in 2002 in various locations. Leaks from the waste pipes and retention tanks were found in April and August 2006; and on the waste treatment station in November 2007. In January 2008 radioactive effluent was inadvertently left in a transfer tank. Above normal releases into the atmosphere were noted in 2006. Areva registered a request to increase maximum emission norms.

The enquiry into the 7 July incident also detected pollution of the water table apparently linked to the storage of military nuclear waste at

Pierrelatte. And it was decided to test the water tables around all French power plants. Frederic Mariller of Greenpeace said in a press release on 17 July 2008: "this analysis must not stop at the nuclear plants but must be widened to all nuclear sites: to processing sites (such as Cadarache, Marcoule, or La Hague), to disused uranium mines (such as Bessines), to military sites (such as Valduc), and to waste-stocking centres, notably in the Manche region and at Soulaines."

But things have far from improved since. Cyril Bouche and his colleagues at the Tricastin nuclear plant say that the state-owned utility EDF, which has expanded into the United States and Britain, is cutting costs and cutting corners, and conditions have been deteriorating over the past 5 to 10 years [4].

"To-day France is selling reactors abroad but it should first put its own house in order," ssid Bouche, the only one of the 10 workers interviewed by Reuters prepared to be identified. The French government has put forward state ownership of the nuclear sector as a guarantee of safety, but the former monopoly EDF subcontracts 80 percent of maintenance to firms such as Vinci, Areva, GDF, Suez or Bouygues.

EDF denies subcontracting means skimping. "We subcontract because we have very specialized activities," said Philippe Gaestel, head of industrial strategy at EDF. "This means we have specialists and competencies that we couldn't have internally."

If serious failures of safety maintenance are occurring in the world's leading nuclear nation, how much worse elsewhere?

NUCLEAR SAFETY UNDER THE SPOTLIGHT

While world leaders were falling over themselves signing up to the nuclear renaissance [5] (see Chapter 3), critics have been quick to remind them of the accidents at Three Mile Island in 1979 and Chernobyl in 1986.

At the Three Mile Island power station near Harrisburg, Pennsylvania, in the United States, a cooling malfunction caused part of the core of a nuclear reactor to melt down, releasing an estimated 43 000 Curies of radioactive krypton gas and under 20 curies of the particularly hazardous iodine-131 to the environment [6].

The disaster at the Chernobyl plant near Pripyat in the Ukraine of the former Soviet Socialist Republic was the worst nuclear accident in history. A nuclear reactor exploded (several times) and caught fire, sending a plume of highly radioactive fallout into the atmosphere that contaminated an extensive geographical area [7]. The fallout was 30 to 40 times that released by the atom bombs of Hiroshima and Nagasaki in Japan during World War II. Some 336 000 people were evacuated and resettled. A 2005 report prepared by the Chernobyl Forum, led by the International Atomic Energy Agency and World Health Organization attributed to the Chernobyl incident 56 direct deaths and an estimated 4 000 extra cancer cases among the approximately 600 000 most highly exposed, and 5 000 among the 6 million living nearby.

The UK government has persistently dismissed childhood cancer clusters around nuclear power stations. It wilfully misinterprets a study commissioned by the German Government that found a correlation between the distance a child lives from the nearest nuclear plant and its risk of developing leukaemia (see Chapter 1).

Given the poor safety records of the nuclear industry even in the top nuclear nation France, who can guarantee that accidents on the scale of Chernobyl will not happen again with the proliferation of new power stations and especially while old power stations are being extended beyond their intended, safe lifetimes?

NO PROTECTION AGAINST SABOTAGE

In response to the tabling of two new reactors and the refurbishing of old ones in Ontario, Canada, a detailed assessment of nuclear accidents and malfunction was carried out by Gordon Thompson of the Institute for Resource and Security Studies at the Massachusetts Institute of Technology [8]. The assessment revealed a litany of design faults in nuclear reactors that fail to protect the public adequately against accidents and malfunction due to human error, mechanical hitches, or external events such as tornados and earthquakes. In particular, there is no protection against malevolent or terrorist attacks. This applies to both existing nuclear reactors and "Generation III" reactors in the pipelines or under construction.

Neither international nor national safety guidelines require such safe designs. Thompson is especially critical of the regulator's and industry's concept of "risk" defined as a product of a number indicating the consequence of an event and another number indicating its probability of occurrence, arguing that equal levels of risk should be equally acceptable to the public.

"That argument is not a scientific statement, it is, instead, dogma representing a particular set of values and interests." Thompson wrote. The reason is that the public may be more concerned about the potential for a high-hazard, low-probability event than a low-hazard, high-probability event at the same level of risk. "That concern can reflect a legitimate set of values and interests, scepticism about estimates of low probability, doubt about the complexity of consequences can be represented by simple indicators, and recognition that new phenomena can come into play when thresholds of consequence are exceeded."

CAN NUCLEAR POWER BE SAFE?

In the 1980s, the reactor vendor ASEA-Atom developed a preliminary design for an "intrinsically safe" commercial reactor known as the Process Inherent Ultimate Safety (PIUS) reactor which was described as follows.

"The basic design of today's light water reactors evolved during the 1950s when there was much less emphasis on safety. Those basic designs held certain risks, and the control of those risks led to an increasing proliferation of add-on systems and equipment ending up in the present complex plant designs, the safety of which is nevertheless being questioned. Rather than to continue into the 'blind alley', it is now time to design a truly 'forgiving' light water reactor in which ultimate safety is embodied in the primary heat extraction process itself rather than activated by add-on systems that have to be activated in emergencies. With such a design, system safety would be completely independent of operator actions and immune to malicious human intervention."

The PIUS design goal was "complete protection against core melting or overheating in case of any credible equipment failure, natural events such as earthquakes and tornadoes, reasonably credible operator mistakes, and combinations of all those. In addition, the design should protect against inside sabotage by plant personnel completely knowledgeable about reactor design, terrorist attacks in collaboration with insiders, military attack, as by aircraft with 'off-the-shelf' non nuclear weapons, and abandonment of the plant by the operating personnel.

Such a PIUS light-water reactor was indeed designed by ASEA-Atom that would cost no more than a conventional plant with the same generation capacity. But to-date no PIUS plant has been ordered.

Another attempt at improving nuclear reactor safety was made in 1991 in a study conducted at the US Oak Ridge National Laboratory, which put together a list of characteristics of 'PRIME' reactors, with safety features that are passive, resilient, inherent, malevolence-resistant, and extended, i.e., remaining in a safe state for an extended period after an accident or attack. The study identified several types of reactors in various states of development as PRIME, but did not set a framework of indicators and criteria that could be used to assess the comparable merits of those reactors to determine if they belonged in the PRIME category.

During the past decade, Generation IV reactors have been proposed that use 'closed fuel cycles' to extend the life of uranium reserves, but these remain on paper as long-term strategies to be developed over the next several decades while Generation III reactors are constructed. The European Commission concedes that Generation III reactors would not meet criteria for sustainability [9] (see Chapter 6), let alone safety.

The reactor is not the only source of serious hazard in case of accidents. The Canadian Environmental Assessment Agency (CEAA) identified three categories of accidents and malfunctions: those directly involving the nuclear reactor such as serious damage to the reactor core; conventional accidents and malfunctions that result in chemical or radioactive releases not directly involving the reactor core and may include those associated with nuclear fuel, and malevolent acts involving fires, explosions, punctures, aircraft crashes that could result from sabotage or terrorist actions..

SPENT FUEL A MAJOR HAZARD

The spent nuclear fuel now stored on site in nuclear power stations is another source of major hazard. Large amounts are stored under water in pools next to the reactors. Those pools currently use high-density racks to maximise the storage space. Unfortunately this makes cooling less effective especially if water were lost from a pool. Several studies, including one from the US Nuclear Regulatory Commission (NRC) [10] (see Chapter 6) have come to the conclusion that loss of pool water could lead to spontaneous ignition of the zirconium alloy cladding of the most recently discharged spent fuel assemblies. The resulting fire would spread to adjacent fuel assemblies and propagate across the pool. It would be difficult if not impossible to extinguish the fire once it had started. Spraying water would make it worse because of an exothermic (heat producing) reaction between steam and zirconium. A fire in the spent fuel storage pool would release huge volumes of radioactive gases to the atmosphere, just as in the case of fire in the reactor core, including a large proportion of the radioactive cesium-137, which is water-soluble and extremely toxic in minute amounts. Loss of pool water could happen in various ways, such as the failure of pumps or valves, piping failures, an ineffective heat sink, a local loss of power, and malevolent acts. According to the NRC Report [11], a fire in the spent fuel pool at a reactor like Vermont Yankee in Pennsylvania, USA, which stores 488 metric tonnes of spent fuel, would cause 25 000 fatalities over a distance of 500 miles *if evacuation were 95 percent effective.* But that evacuation rate would be almost impossible to achieve.

It gives us little comfort to know that none of the commercial nuclear power plants now operating around the world can resist malevolent attacks, not because it is impossible to design such plants, but because the industry has simply chosen not to do so, and the International Atomic Energy Agency, responsible for among other matters, the development of criteria for the safety and security of nuclear power plants, does not explicitly require plants to be safe against malevolent attacks. The Canadian Nuclear Safety Commission's criteria are no better. Neither agency addresses potential releases from stored spent fuel.

Not surprisingly, none of the proposed Generation III nuclear reactor designs in Ontario or elsewhere gives adequate protection against malevolent attacks and may also fail other safety design criteria.

There is practically no defence against a range of "credible" attacks on existing nuclear plant. Among the possibilities mentioned is [8] "a small, general aviation aircraft laden with explosive material, perhaps in a tandem configuration in which the first stage is a shaped charge." A shaped charge is one that is shaped to deliver all the energy of explosion in one direction.

Devastating as they are, it won't be safety concerns that abort the nuclear rebirth, but the economics [12] (see Chapter 5).

5

NUCLEAR INDUSTRY'S FINANCIAL & SAFETY NIGHTMARE

UK's unfolding nuclear catastrophe

Selfield Site

Sellafield has become "the most hazardous place in Europe", according to George Beveridge, Sellafield's deputy managing director

VOODOO ECONOMICS & NUCLEAR DOOM

Paul Brown, environmental correspondent of The Guardian newspaper in Britain, produced a detailed report documenting why it is not possible to achieve what the UK Government says it will do, build a new generation of nuclear stations without public subsidy [1], which is essentially what the Government has repeated in its recent White Paper (see Chapter 1).

It appears impossible to have new nuclear build in the United States even with extremely generous public subsidy [2] (see Chapter 3). The situation is the same in Germany and the world over, including the UK. According to Hermann Scheer, member of the German Parliament since 1980, the nuclear industry is the result of [3] "a gigantic machine powered by political subsidies and privileges. Everywhere, it gets tax breaks for nuclear fuels, exemptions from liability insurance, as well as favourable loans and investment subsidies." But that's not all. Governments all over the world have already subsidized US$ 1 trillion on research and development of nuclear energy alone, 20 times the amount that has been invested in renewable energies.

Brown's report exposed how badly the nuclear industry has performed over the entire 50 years of unfulfilled promises, and the escalating bill to the taxpayer.

The UK nuclear industry, like that in the US [2], has never completed any project on time or on budget and has saddled the nation with a mammoth nuclear fuel reprocessing complex at Sellafield that's a financial as well as safety nightmare.

British Energy, the commercial company privatised in 1996, soon ran into serious financial trouble [4] (see Box 1), and had to be taken over by the government. That meant the taxpayer has essentially underwritten all its debts and liabilities so the company can never go bankrupt. Brown remarks: "This commitment dwarfs the risk to the taxpayer of the Northern Rock nationalisation [which precipitated the financial crisis that has plunged the nation into its current deep recession]." It means paying for the maintenance and decommissioning of ageing nuclear power stations, and worst of all, the upkeep of the Sellafield nuclear reprocessing complex.

So why is the UK government so keen to build new nuclear stations? Its own figures show that a new nuclear power programme will cut gas imports by only seven percent and carbon emissions by four percent. Yet the programme for four gigantic new stations will get policy encouragement and public subsidy on the false claim that Britain needs them for energy security and reducing carbon emissions.

It will take 10 to 20 years before the first new nuclear stations can be built and producing power in Britain. By that time, the liabilities will be so great that the Government will have to renationalise British Energy, Brown says.

The crisis may come much sooner, and British Energy may have to start closing some of its nuclear stations permanently because the only remaining storage space for spent fuel at the

Box 5.1
BRITISH ENERGY
British Energy, the UK's largest electricity provider, was established and registered in Scotland in 1995 to operate the 8 most modern nuclear stations, two advanced gas-cooled reactors (AGRs) from Scottish Nuclear and five AGRs and one pressurised water reactor (PWR) from Nuclear Electric. The remaining Magnox power stations from these two companies were transferred to Magnox Electric which later became the generation division of British Nuclear Fuels (BNFL). British Energy was privatised in 1996 and bought the 2 GW Eggborough coal fired station from National Power in 2000.

The company ran into financial trouble in 2002, when it first approached the British government for financial aid. In September 2004, the government bailed out the company with over £3 billion investment, and took over all its liabilities.

Sellafield complex in Cumbria is running out.

Three of the four new reactor designs being put forward for UK construction have never been built. The only proposed "Generation III" plant under construction is Areva's EPR, an advanced pressurized water reactor (also under consideration in Ontario) in Finland. The Finnish reactor, Olkiluoto 3, a 1 600 MW EPR was due to generate electricity in 2009. Delays have dogged the construction from the outset and its completion date has been repeatedly put back. In January 2009, the completion date was pushed forward to 2012, with Areva and the Finnish electricity provider blaming each other for the new delays [5].

NIGHTMARE AT SELLAFIELD

Sellafield's nuclear complex consists of five important operations: two reprocessing plants, the MOX (mixed oxide fuel) plant, the evaporators, and the vitrification plant (that turns highly dangerous radioactive liquid waste into safer glass). With more than 10 000 employees, the massive complex is in crisis. Its reprocessing works and plutonium fuel plant are all failing, costing the taxpayer £3 billion a year and rising [1].

The taxpayer already faces £73 billion clean-up bill for decommissioning existing nuclear plants, most of that will be spent in Sellafield.

Reporting for the BBC, David Shukman wrote of his visit to Sellafield [6]: "I saw for myself one of the "ponds" in which an unknown mass of radioactive material was dumped in the 1950s.... Beneath the unruffled surface of the water lies an unrecorded collection of rusting metal containers holding radioactive waste, including spend fuel rods…Beside it, workers are constructing a vast new building to handle the materials when a retrieval operation eventually gets under way."

Jim Morse, a senior director at Sellafield sums up the sorry state of affairs in record keeping: "We still have a lot to discover, we haven't started waste retrieval in those parts of the estate where the degradation and radioactive decay has been at its greatest." Morse also said the cost of cleanup could go up even further by "some billions". That's not the only problem.

The flagship Thorp reprocessing plant, built to extract plutonium and unused uranium from spent nuclear fuel [7] was closed for three years from 2005, and remains under severe operating restrictions and cannot complete its long-overdue contracts to process spent foreign fuel into MOX fuel [1]. The closure of the elderly Magnox reprocessing plant has been postponed, leaving the UK unable to meet its international commitments to cut radioactive discharges into the Irish Sea. The plants for dealing with the residue of reprocessing – the volatile and dangerous heat-producing high-level liquid waste – fail to work as designed, causing the whole Sellafield production line to seize up. The MOX plant is supposed to make money by turning plutonium and uranium into new fuel, but has been a technical and financial disaster. The fuel was supposed to be the safe way of returning tonnes of plutonium recovered during reprocessing to its country of origin. This plan has failed, but the Government has no policy for dealing with the ensuing economic and political crisis. As a result, Sellafield is becoming the world's nuclear dustbin, because foreign nuclear wastes are not being repatriated.

As the UK Government announced plans for a new generation of nuclear plants in April 2009, Sellafield has become "the most hazardous place in Europe", according to George Beveridge, Sellafield's deputy managing director [8]. Greenpeace campaigners dub the disused plutonium reactors on site a "slow motion Chernobyl".

Sellafield's nuclear complex is in crisis. Its reprocessing works and plutonium fuel plant are all failing, costing the taxpayer £3 billion a year and rising. The taxpayer already faces £73 billion clean-up bill for decommissioning existing nuclear plants, most of tha will be spent in Sellafield

As Peter Bunyard wrote in 2005 [9], many critics of MOX within and outside the nuclear industry have repeatedly pointed out that the gains are far outweighed by economic and environmental problems. "In France, reprocessing spent fuel to extract plutonium for MOX fuel manufacture will save no more than 5 to 8 per cent on the need for fresh uranium. Meanwhile, as experience in both France and Britain has shown, reprocessing spent reactor fuel leads to a hundredfold or more increase in the volume of radioactive wastes. In the end, all the materials used, including tools, equipment and even the buildings become radioactive and have to be treated as a radioactive hazard."

It is highly questionable whether the use of MOX fuel will actually reduce the amount of plutonium. Reactors have to be modified to take MOX fuel, and it is estimated that supply exceeds demand by a factor of two. Meanwhile MOX fuel contains up to 5 percent plutonium and is ideal for terrorist, as the plutonium can be easily extracted to make bombs.

WORLD'S NUCLEAR WASTE DUMP

While Britain piles up its own and foreign nuclear waste, there are currently no plans or sites for a repository to store or dispose of it [1]. The earliest dates for a deep underground intermediate waste repository are notionally 2045 for high level waste 2075. In reality there are no plans for either. Storage space for spent fuel is also running out at Sellafield. Spent fuel assemblies are stacked three deep at the reception ponds and are already a major source of hazard [10] (see Chapter 4). If Sellafield cannot take any more spent fuel, then British Energy's reactors will have to shut down

In the meantime, an average of 300 tonnes of spent fuel has continued to be delivered to Sellafield each year and none has been cleared through reprocessing in order to free storage space for those continued deliveries. There is an increasing backlog of both spent fuel and all forms of waste. UK's Nuclear Decommissioning Authority revealed in June 2007 that there were 30 000 tonnes of uranium and 100 tonnes of plutonium in store, but no policy for managing the material in the long term

In the context of a massive new nuclear building programme, Sellafield is not just a huge embarrassment but a graphic demonstration of how expensive mistakes can be. The National Audit Office said in 2008 that it is creating an "apparently ever escalating bill" for the taxpayer.

MASSIVE LIABILITIES DISCOUNTED

In April 2007, a cost benefit analysis by the Department for Business, Enterprise and Regulatory Reform (BERR) concluded that nuclear power is likely to cost 4.8 pence per kilowatt hour to produce, provided all future nuclear waste costs are discounted. British Energy's undiscounted liabilities in 2007 were £14.5 billion, more than double the amount in the liabilities fund designed to pay decommissioning costs [1]. The nuclear liabilities fund is invested in a supposedly ring-fenced fund, like a pension fund for nuclear facilities. But in the past those funds have been raided by the nuclear industry to build new nuclear facilities, such as Sizewell B, and the money has evaporated.

The government has pledged this will not happen again and the discount rate of 3 percent is based on the assumption that the liabilities fund will grow at the rate of 3 percent. The theory is that by the time decommissioning is necessary the fund will neatly pay for everything. The National Audit office and the House of Commons Committee on Public Accounts concluded: "the taxpayer is still exposed."

Liabilities could easily exceed assets when prices are volatile. In particular, the price of uranium is rising, and experts all say that the supply of good quality uranium is finite, which is also one major reason nuclear power is unsustainable [11] (see Chapter 7). A shortage of suitable uranium would do to nuclear fuel when the price of oil has done to the cost of running the family car. In January 2008, the cost of uranium had gone up to US$95 a pound, compared with $85 a pound in March 2007. This would drive up nuclear fuel costs by £146 million a year.

It is quite clear that the British government has been doing everything to make nuclear power look economically competitive, and will give all the overt and covert subsidies required to make it happen. The new breed of nuclear power stations are going to be among the biggest power plants in Britain and will be located far away from where most of their electricity will be used. This will require a large investment in the national grid adding further to the financial drain and the inefficiency of the nuclear option.

6

OLD NUCLEAR CASH COWS
COMPROMISE SAFETY

"Nuclear renaissance" a convenient charade while industry milks old nuclear cash cows to drain the public coffers and endanger the nation

While researching the present series of articles on nuclear energy, it began to dawn on me that the "nuclear renaissance" may be nothing more than a convenient charade put on by the nuclear industry to distract attention away from its enormous debt to the nation and at the same time allow it to milk the old nuclear "cash cows" for all they are worth, i.e., make huge profits from old, unsafe, nuclear stations.

Just how much is owed to the British taxpayer is made clear in the report [1] by environment correspondent of *The Guardian* Paul Brown (see Chapter 5). The largely private company British Energy is making profits while the taxpayer foots the industry's bills and liabilities. British Energy's profit stood at £243 million for the first half of 2007 [3], Since 2004, the British taxpayer has underwritten all its debts so it could never go bankrupt, and is now paying £3 billion a year just to keep the rapidly failing Sellafield nuclear fuel reprocessing complex open. The cost of keeping Sellafield open is escalating fast, but the alternative of closing it down would be financially much worse, at least for the immediate future. It would mean no nuclear power station could operate, and the cost of decommissioning will have to be faced, which currently stands at £73 billion, much more than what it would cost in the United State (see below). That is largely because Sellafield has become the world's nuclear dustbin through importing foreign spent fuel it is unable to reprocess or repatriate. British Energy's profit, even at best, is a pittance compared with its liabilities of £14.5 billion in 2007; and enforced plant closures due to safety concerns are eroding the profit. It slumped 66 percent in the three months to the end of June 2008 as electricity production dropped by a quarter due to the closure of the Hartlepool and Heysham 1 reactors following the discovery of corroded wiring [4].

The threat of closure hangs over all British Energy's ageing reactors because of safety faults, for example, distortion of graphite blocks or corrosion, both of which have already been identified as life-limiting problems [1]. The closure of Mox plant Thorp on the Sellafield site could add billions to the liabilities. So far the company and the UK Government are avoiding these eventualities by extending the life of Thorp to at least 2015, along with extensions for the three advanced gas-cooled reactors (AGRs) that were due to be closed soon. Despite boiler cracks, Hinkely Point in Somerset and Unterston on the Ayrshine coast due to close in 2011, had their lives extended to 2016 in December 2007. Because of safety fears, they were operating at an uneconomic 60 percent capacity at the beginning of 2008, but the company hoped to raise this to 70 percent and get them back into the black. Dungenese B in Kent, due to close in 2008, has already had its life extended to 2018, Next in line for extensions are Hartlepool on Teeside, and Heysham 1 in Lancashire, both due to close in 2014. It is only by extending the lifetime of the nuclear power stations and Thorp that British Energy and the Government are spared having the liabilities of the industry fully exposed to public view.

Vermont Yankee power station

"CASH COWS" GALORE

The fact that new nuclear power stations make little economic sense does not mean that old ones are not profitable, especially in the USA. As Christian Parenti pointed out in The Nation [5], "these nightmarishly complex radioactive boondoggles have recently been turned into cash cows."

Beginning in the 1990s, most US energy markets were deregulated one state, one region at a time. This allowed utilities to pass on to rate payers the "stranded costs", i.e., the outstanding mortgage payments of the nuclear power plants.

Perhaps the most egregious example of that occurred in California. In 1996, the State Assembly passed legislation written by utility lobbyists that allowed Southern California Edison and Pacific Gas & Electric to hold rates high as prices dropped nationally. The two utilities were to receive $28 billion over four years. This money would pay off the stranded costs of the Diablo Canyon and San Onofre atomic plants. Halfway through the deal, the California power crisis hit and deregulation was suspended. But the state floated bonds to soak up the remaining stranded costs.

Similar deals were struck across the country. Relieved of old debts, the nuclear plants with relatively low overhead costs became valuable assets. A new generation of firms began buying them up, often for a song. By 2002, ten companies owned seventy of the country's 104 reactors, among them are Exelon, Entergy and Dominion Resources.

Vermont Yankee, a thirty-five-year-old reactor was bought by Entergy seven years ago for a mere $180 million, about half what it would cost to build a coal plant or wind farm with the same generating capacity. Entergy is now trying to run the power station as hard and as long as possible to maximise profits. In 2006 it received approval to increase power output by 20 percent. This means the plant operates with 20 percent more pressure, heat and flow. And in just one year it earned Entergy $100 million in profits. Over the last decade, almost all US nuclear power plants have received uprates; but few match Vermont Yankee's 120 percent capacity.

If exposed to air for more than six hours, spent fuel rods spontaneously combust, spewing highly poisonous radioactive isotopes far and wide. This spent fuel will be hot for 10 000 years

NEXT BIG ACCIDENT WAITING TO HAPPEN

Just after the uprate, one of Vermont Yankee's twenty-two cooling towers collapsed [5]. Entergy officials said the collapse "baffled" them. A spokesperson admitted that their "inspections were not effective enough." Gregory Jaczko at the Nuclear Regulatory Commission (NRC), admitted that the collapse "didn't look good", but went on to reassure the public that the plant is essentially safe.

Entergy has since petitioned the NRC to extend its operating license so that it can run the old plant for twenty years longer than was intended. The current license is due to expire in 2012.

Nationally, forty-eight facilities have had their licenses extended. In fact, despite critics' arguments that ageing plants pose serious dangers, no license renewal requests have ever been turned down.

Diana Sidebotham, an antinuclear activist in Putney, Vermont, thinks Entergy and the NRC are courting disaster. In 1971 Sidebotham helped found the New England Coalition on Nuclear Pollution, and she has been trying to shut down nuclear plants ever since.

"One of these days a plant will blow," says Sidebotham. "And when it does, it will cause a great many deaths and widespread suffering, not to mention extraordinary economic damage."

In 2002, the Davis-Besse Nuclear Plant in Ohio was forced to close for two years after inspectors found "a football-sized corrosion hole" in the reactor's six-inch-thick steel cap. The plant was "very close" to a major accident.

Activists like Sidebotham say the real issue is not how to build more nuclear plants but how to handle the old, decrepit ones and their huge stockpiles of radioactive waste; the same problem as in the UK and elsewhere. Most of the atomic plants in the world are reaching the end of their lifespan. In the US, 17 have been decommissioned. And increasingly the question is what to do with the accumulated waste, the extremely radioactive spent fuel rods [2]. If exposed to air for more than six hours, spent fuel rods spontaneously combust, spewing highly poisonous radioactive isotopes far and wide. This spent fuel will be hot for 10 000 years.

Since 1978, the Department of Energy has been studying Yucca Mountain in Nevada as a possible permanent repository for atomic waste. But intense opposition has held up those efforts [5]. In February 2009, the Obama administration effectively killed this option (see Chapter 1). In the meantime, the spent fuel is stored at the old power plants, in pools of water lying near great cities, on crucial river systems, in small rural towns. These pools are potentially a far greater risk than a reactor meltdown. Terrorists might attack and drain them, by driving a truck bomb or crashing an explosive-laden plane into them.

Parenti recalls [5] how, just after 9/11, when security at nuclear plants was supposed to be at its peak, lead pellets started raining down on the nuclear reactor's containment structure and guard shack at Maine Yankee, in Wiscasset. (The plant has since been decommissioned.) A group of four armed men in camouflage had infiltrated into a swamp and were firing weapons from the reeds. These men turned out to be local duck hunters who had no idea they were shooting at the nuclear power plant. This episode proved just how easily an attack could be made.

Activists demanded, and got, a safety review, which led to a "shockingly" blunt NRC Report on Spent Fuel Pool Accident Risk at Decommissioning Nuclear Plant (NUREG-1738) published in February 2001 [6]. The report found that containment structures, such as that at

Vermont Yankee, “present no substantial obstacle to aircraft penetration.” A fire in the spent fuel pool at a reactor like Vermont Yankee (which stores 488 metric tonnes of spent fuel) would cause more than 25 000 cancer fatalities over a distance of 500 miles *if evacuation* were 95 percent effective. But that evacuation rate would be almost impossible to achieve.

The NRC claimed to have the threat of terrorism under control, but for reasons of national security it could not explain how. After 9/11 it admitted, “At this time, we could not exclude the possibility that a jetliner flying into a containment structure could damage the facility and cause a release of radiation that could impact public health.”

Parenti concludes [5]: “This much seems clear: a handful of firms might soak up huge federal subsidies and build one or two overpriced plants. While a new administration might tighten regulations, public safety will continue to be menaced by problems at new as well as older plants. But there will be no massive nuclear renaissance. Talk of such a renaissance, however, helps keep people distracted, their minds off the real project of developing wind, solar, geothermal and tidal kinetics to build a green power grid.”

No doubt, talk of a nuclear renaissance also helps keep people distracted to allow the industry milking the old nuclear cash cow while draining the public coffers and endangering the public.

BITE THE BULLET & OPT OUT NOW

It is clearly very costly to give up on nuclear power, but much more costly not to do so. The cleanup costs of decommissioning in the UK stood at £73 billion in 2008 [1], and no permanent storage site has been identified for the mountains of nuclear wastes. But the industry is already a huge drain on the taxpayer costing £3 billion a year and rapidly rising, while more and more nuclear wastes keep piling up to add to the cost of decommissioning..

In the US, even if no new reactors are built, getting rid of the country’s nuclear waste would cost $96.2 billion plus a major expansion of the Yucca Mountain waste dump beyond limits imposed by Congress [7], the Department of Energy said.

This revised cost estimate came as Senator John McCain renewed his call for building as many as 45 new power reactors by 2030. The new estimate is $38.7 billion more than anticipated by the Department of Energy in 2001, and is because current reactors are allowed to operate longer and so the Yucca site will have to accept more waste. Congress has limited it to 77 000 tons.

Commercial power plants currently have about 64 000 tons of used reactor fuel at power plants in 33 states awaiting shipment to Yucca Mountain, with the amount growing at the rate of 2 000 tons a year.

Existing power plants are a huge drain on taxpayer’s money while posing monumental threats to public safety and national security. We have little choice but to bite the bullet and opt out of nuclear power. We must stop the nuclear renaissance charade and start decommissioning old plants before the nuclear nightmare gets considerably worse. There is no future in the nuclear option as study after study makes clear [8] (see next chapter).

Time and resources are both running out, and we need to invest them instead in truly sustainable, renewable, and safe energies [9] as we already made clear in our 2006 Energy Report.

In the US, even if no new reactors are built, getting rid of the country’s nuclear waste would cost $96.2 billion plus a major expansion of the Yucca Mountain waste dump beyond limits imposed by Congress

7

THE NUCLEAR BLACK HOLE

Study after study confirms the nuclear option is inherently unsustainable, unsafe, and uneconomic

NUCLEAR UNSUSTAINABLE

Veteran ecologist Peter Bunyard was spot on in his article [1] pointing out that nuclear is not a renewable energy, and apart from being extremely uneconomical and unsafe, it is highly unsustainable in terms of savings on energy and greenhouse emissions; in fact, worse than a gas-fired electricity generating plant as high grade uranium ore is depleted and available ore falls below 0.02 percent. This has been amply confirmed by studies carried out since.

A report published in 2008 [2, 3] shows that in order to replace fossil-fuel energy use and meet the future energy demands, nuclear energy must increase by 10.5 percent each year from 2010 to 2050. This large growth rate creates a "cannibalistic effect", where nuclear energy must be used to supply the energy for future nuclear power plants.

Joshua Pearce, a physicist at Clarion University of Pennsylvania, found he cannot balance the books if the nuclear power option is taken in preference to renewable energy sources. The enormous amounts of energy needed for mining and processing uranium ore, and building and operating the power plant simply cannot be offset in a high growth scenario. In particular, growth limits are set by the grade of uranium ore available, confirming earlier studies [1] (see later).

As is well known, on account of safety reasons and scale of operation, nuclear plants are far away from users and transmission over long distances incurs a loss of at least 6 percent of the electricity generated. For the same reasons, most of the heat produced, 60 percent or more, is also wasted. This waste heat, Pearce reminds us, directly warms the earth.

The lifecycle assessment (LCA) Pearce carried out shows that nuclear energy costs between 16 to 55 g CO_2e/kWh, based on current practice in the United States with regard to mining and enrichment of uranium ore, and does not include reprocessing or decommissioning, but includes spent-fuel disposal and the deconversion of depleted uranium (back to U3O8). It falls short of a genuine "cradle-to-grave" LCA [4] (see Chapter 12).

The estimated energy payback time – the time it takes to generate as much energy as is used and to save as much CO_2e as was expended in the complete lifecycle – and the emissions payback time are very dependent on the grade of uranium ore and on the energy mix of the area where the nuclear plant is located. For example, the energy payback time is between 5.5 years and 92 years with the US energy mix, while 1.5 to 12 years are estimated for the European energy mix for a high ore grade of 0.1 percent; the corresponding figures for an ore grade of 0.01 percent are 7 years to infinity (no payback) in the US and 4 to 46 years in Europe. Clearly, these figures are way out of line with those of renewable, sustainable options such as wind and solar [4-6] (see Chapters 13-20), which are immediately available and rapidly gaining ground.

Pearce suggests efforts to be made to improve the efficiency of nuclear power, using only the highest concentration ores and switching to fuel enrichment based on gas centrifuge technology instead of gaseous diffusion, use of combined heat and power generation for nuclear plants and down-blend nuclear weapons stockpiles containing highly enriched uranium to produce nuclear power plant fuel (though that too, is a limited stock)

In the past 12 years, Germany has created an electricity generating capacity of 30 GW under its Renewable Energies Act. In 2007 alone, the new renewable capacity grew so fast that it produced 15 TWh of electricity, which equals the output of two nuclear power plants

NUCLEAR CONTRIBUTION INSUBSTANTIAL

For all the fuss about nuclear energy, it actually accounted for a mere 2.1 percent of the energy used globally in 2006 [7] (see Table 7.1). The nuclear contribution to the world electricity generation was 14.8 percent; and has been slowly declining from a peak of some 17 percent in the early 1990s. In 2008, according to British Petroleum, world nuclear generation decreased by 0.7 percent, making two consecutive years of decline [8].

Since 2006, the world has seen a phenomenal rise in new renewable energy capacity to more than 6 percent (see Chapter 11), and that is the most powerful argument against nuclear energy. In the past 12 years, Germany has created an

ENERGY SOURCE	ELECTRICITY TWh	COMBUSTIBLES MTOE	EJ	FRACTION (%)
nuclear	2808.1		10.109	2.1
hydro	3040.4		10.956	2.3
oil		3889.8	163.37	34.3
natural gas		2574.9	108.15	22.7
coal		3090.1	129.78	27.2
Total traded energy units	5848.5	9554.8	422.36	
traditional biomas *		1243.6	52.23	11.0
modern renewables **	527.7		1.90	0.4
world total	6376.2	10798.4	476.49	100

Table 7.1. Energy available globally in 2006

electricity generating capacity of 30 GW under its Renewable Energies Act. In 2007 alone, the new renewable capacity grew so fast that it produced 15 TWh of electricity, which equals the output of two nuclear power plants [9].

And, as pointed out by Jan Willem Storm van Leeuwen, Senior Scientist of Ceedata Consultancy in Chaam, The Netherlands, nuclear energy cannot reduce the world's greenhouse emissions (or fossil fuel use) by more than 2.1 percent [7]. This sums up the absurdity the "nuclear renaissance", and all the more so when the sums are worked out in detail.

LIFECYCLE ASSESSMENT

By far the most thorough LCA on nuclear energy has been carried out by Jan Willem Storm van Leeuwen and Philip Smith originally in 2005 [10], and subsequently updated and extended by the first author [11] partly in response to critics from the nuclear industry.

The only natural element that undergoes nuclear fission from which nuclear power can be harnessed for use in a reactor is uranium-235 (U-235). This radioactive isotope accounts for 0.71 percent of natural uranium, the remaining is U-238. and with traces of U-234, neither of them fissile (capable of being split). In an operating nuclear reactor, some of the abundant U-238 is converted by neutron capture into plutonium-239, which is fissile.

There are two kinds of nuclear reactors: burners and breeders. In a burner reactor, no more than 0.6-0.7 percent of the atoms in the natural uranium in the fuel can be split. The rate at which U-238 converts into fissile plutonium is less than that at which U-235 and Pu-239 are split. When the fissile content of the fuel in the reactor falls below about 0.8 percent, the fuel has to be replaced by fresh fuel.

In a breeder reactor, more fissile Pu-239 and Pu-241 are formed than are split. Theoretically,

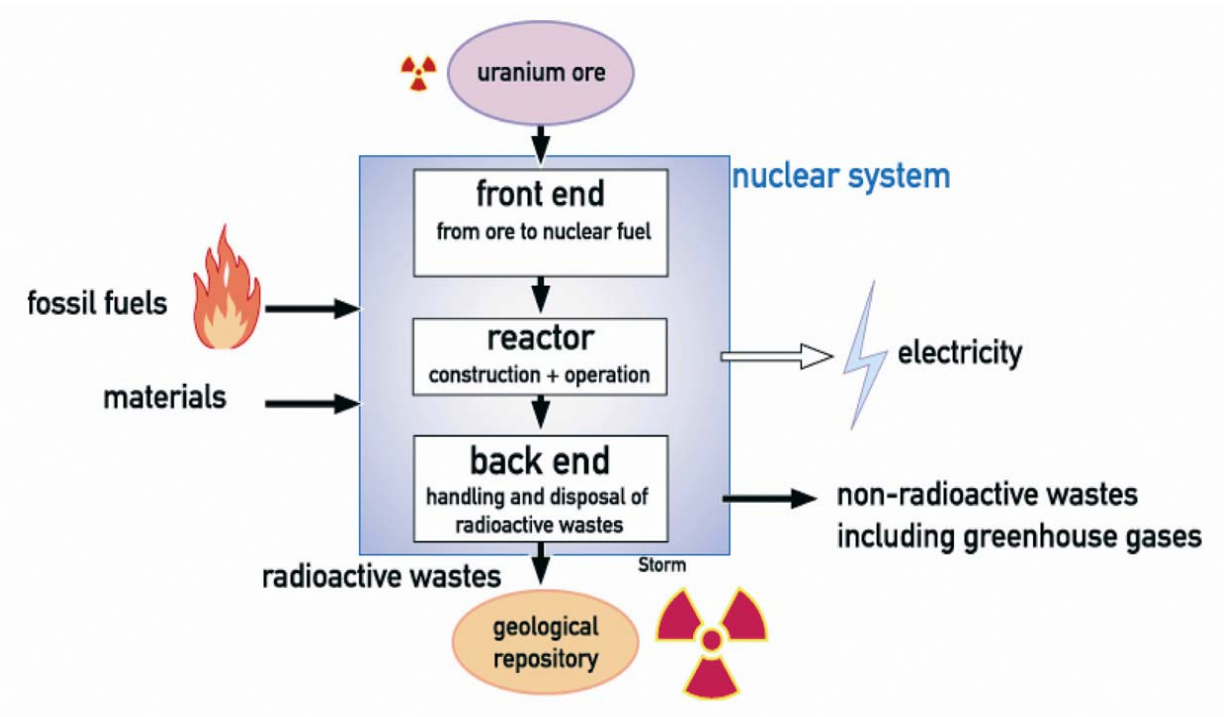


Figure 7.1 Simplified nuclear chain for lifecycle assessment

some 30-60 percent of the natural uranium could be split in this way. But breeder reactors remain technically unfeasible. A breeder reactor is not just a single structure, but involves a reprocessing facility and a fuel fabrication plant in addition; and all three components have to be operating flawlessly and continuously, exactly tuned to the others. If one component fails, the whole collapses. None of the three components has ever been demonstrated to operate as required, and that after 50 years of intensive research efforts and hundreds of billions of dollars invested in seven countries: USA, UK, France, Germany, former USSR and now Russia, Japan and India. Technical hurdles are not the only problems, also safety, economy and the risk of nuclear proliferation and terrorism.

More than 88 percent of world's nuclear reactions are light water reactors, and achieve a lifetime uranium utilization of less than 0.6 percent, which means that for every kg of uranium delivered by the mine, 994 g leave the nuclear reactor as depleted uranium in highly radioactive spent fuel. Advanced 'Generation III' reactors and the Pebble Bed Reactor [12] may reach uranium utilization slightly higher than 0.6 percent, but that remains speculative.

In the once-through mode, no uranium and plutonium are recycled, so spent fuel is not reprocessed. Several studies have concluded that the reprocessing and the use of mixed oxide (MOX) fuel are unjustified on grounds of safety, efficiency and risks of proliferation [1, 13] (see Chapter 4)

The world's nuclear power capacity is 370 GW, which is roughly equivalent to 400 reactors of 1 GW each. A LCA was therefore carried out on a 'reference reactor', a 1 GW light water reactor of current design operating without plutonium recycling operating for a lifetime of 30 years at an average load factor (ratio of output over capacity) of 0.82. The lifetime and load factor assumed are considerably better than what real reactors have achieved so far.

The stages in the nuclear chain at which energy inputs are required are depicted in Figure 7.1 [14].

The 'front end' processes include mining and milling of the uranium ore U_3O_8, conversion into UF6, enrichment by gaseous diffusion or gas centrifuge and fabrication of the fuel assembly.

The 'reactor' processes include construction of

GRADE, G % U_3O_8	YIELD, Y	Eth + Ee TJ/Mg U	Eth TJ/Mg U	Ee TJ/Mg U	m(CO_2) Mg/Mg U	CO_2 EMISSION g/kWh *
10	0.990	0.078	0.025	0.003	1.84	0.04
1	0.980	0.281	0.248	0.033	18.6	0.42
0.5	0.973	0.565	0.499	0.066	37.4	0.84
0.15	0.931	1.97	1.74	0.23	130	2.95
0.10	0.908	3.03	2.67	0.36	200	4.53
0.06	0.872	5.26	4.64	0.62	348	7.86
0.05	0.850	6.47	5.71	0.76	428	9.68
0.04	0.825	8.33	7.35	0.98	551	12.5
0.03	0.775	11.8	10.4	1.4	783	17.7
0.02	0.700	19.6	17.3	2.3	1300	29.4
0.013	0.472	44.8	39.5	5.3	2966	67.0
GRADE, G % U_3O_8	**YIELD, Y**	**Eth + Ee TJ/Mg U**	**Eth TJ/Mg U**	**Ee TJ/Mg U**	**m(CO_2) Mg/Mg U**	**CO_2 EMISSION g/kWh ***
10	0.990	0.066	0.041	0.025	3.08	0.07
1	0.980	0.667	0.411	0.257	30.8	0.70
0.5	0.973	1.34	0.827	0.517	62.0	1.40
0.15	0.931	4.68	2.88	1.80	216	4.89
0.10	0.908	7.21	4.43	2.77	333	7.52
0.06	0.872	12.5	7.69	4.81	577	13.0
0.05	0.850	15.4	9.47	5.92	710	16.1
0.04	0.825	19.8	12.2	7.62	915	20.7
0.03	0.775	28.1	17.3	10.8	1298	29.3
0.02	0.700	46.7	28.7	18.0	2156	48.7
0.013	0.472	107	65.6	41.0	4919	111.2

E_{th} refers to thermal energy, E_e refers to electrical energy.

Table 7.2 Energy and CO_2 costs of mining and milling as a function of uranium grade for soft (top) and hard (bottom) ore

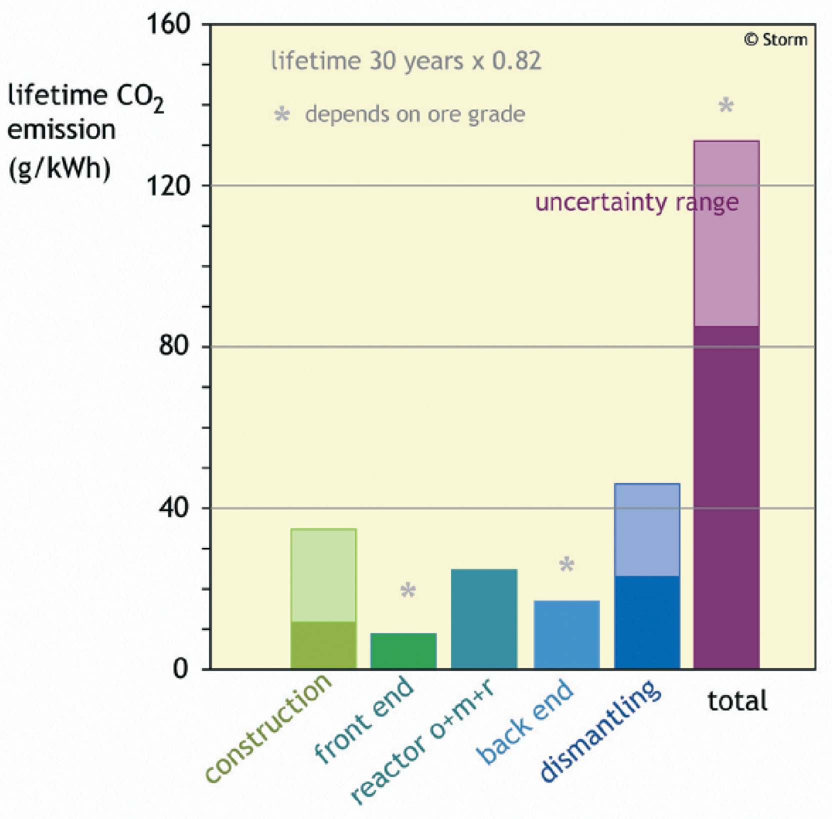


Figure 7.2 The lifetime CO_2 emission for the reference nuclear system

the power plant and operation where the fuel is burnt and the heat produced used to drive a turbine/generator to produce electricity. Operation costs includes controlling the fission process so it doesn't go 'critical' as in an atom bomb [1], and making up materials and chemical and non-radioactive waste management.

The 'back end' processes are the most demanding, and also most often ignored. They include retrieving spent fuel, deconversion, and storing it at the reactor site for further reprocessing or disposal. Nuclear wastes from power stations will remain dangerous to humans for generations, which is why they have to be stored permanently. Also included is decommissioning the power plant once its useful and safe lifetime is over.

The nuclear industry is effectively ignoring decommissioning, which involves a long drawn-out and demanding series of steps. First, the reactor has to be cleaned up and safeguarded for a cooling period of 30-100 years after closedown. The radioactive parts of the nuclear island have to be dismantled after cooling, and the radioactive scrap and rubble packaged to prevent illegal trade in radioactive scrap, which is already a problem today. The spent fuel removed from the reactor has to be stored for at least 30 years in heavily protected and safeguarded facilities, bearing in mind that one reactor produces during its lifetime an amount of radioactivity equal to about 10 000 exploded nuclear weapons; and corrosion and leaking fuel pins may pose a problem in addition to the danger of terrorist attacks. The spent fuel then has to be packaged in containers able to last for many thousands of years in contact with hot and salty water under continuous nuclear radiation. A stable geological repository has to be constructed to isolate the spent fuel from the biosphere for hundreds of thousands of years. Over a period of decades, the canisters with the spent fuel will be placed into boreholes in the floors of the numerous galleries in the repository, and when fully occupied, the galleries and access tunnels have to be filled up with bentonite and closed forever.

At some time between 2066 and 2076, when average ore grade decreases to 0.02 percent or less, uranium fuel reactors would fall off the 'energy cliff' i.e., consume more energy than they generate, and produce more CO_2 emissions than a gas-fired power plant

The reference reactor for the LCA produces about 20 Mg spent fuel a year. Assuming a lifetime of 30 years, each reactor produces about 600 Mg spent fuel.

Assuming the world nuclear fleet to be 400 reference reactors, 8 000 Mg spent fuel has to go into storage each year worldwide. Even if exceedingly large repositories will be constructed, larger than the Yucca Mountain repository in the USA, a new repository has to be opened every ten years, and a full one closed up.

In addition, the uranium mine has to be reclaimed, an area of up to about 100 km^2. The tailings, containing large amounts of chemically and physically mobilized radioactive species, have to be isolated from the groundwater and the air. Existing reprocessing plants such as Sellafield in the UK and La Hague in France will have to cleaned up and dismantled. This activity will be extremely demanding. In the UK, the estimated costs are about £73 billion and rising [15] (see Chapter 4).

None of the decommissioning processes is operational at this moment, and no satisfactory practical solutions for a number of the problems have been found during the past 40 years. Geological repositories exist still only on the drawing boards.

So, the energy requirements and CO_2 emissions of the back end decommissioning processes are estimated by comparison with similar industrial processes where data do exist.

Figure 7.2 presents the summary of LCA for a uranium ore grade of 0.15 percent, which is the mean value of available uranium ore grade for the world in 2005 [16]

As can be seen, the lifetime greenhouse emission is well over 85 g CO_2e/kWh or more. And this is likely to go up considerably as good grade uranium runs out and poorer ores have to be mined.

COSTS RISE EXPONENTIALLY AS ORE GRADE DROPS

The grade of uranium ore used is critical in determining the lifetime greenhouse emissions and energy savings. The yield of uranium (proportion of available uranium extracted from the crude ore) decreases roughly linearly as the ore grade goes down; the amount of energy needed for extracting in mining and milling, however, goes up *exponentially*, as does carbon emission (see Table 7.2).

Thus the energy expenditure and greenhouse emissions for mining 0.15 per are: 0.23 TJ/Mg U and 2.95 g CO_2e/kWh for soft ore; and 1.80 TJ/Mg U and 4.89 g CO_2e/kWh for hard ore. By the time the uranium grade has decreased to 0.02 percent, the corresponding values will be ten-fold: 2.3 TJ/Mg U and 29.4 g CO_2e/kWh for soft ore; and 18.0 TJ/Mg U and 48.7 gCO_2e/kWh for hard ore. If 0.015 percent ore is to be mined, the values will more than double: 5.3 TJ/Mg U and 67.0 g CO_2e/kWh for soft ore; and 41.0 TJ/Mg U and 111.2 g CO_2e/kWh for hard core. These figures make nuclear no better than a gas-fired electricity generating plant.

According to the Oxford Research Group [17], just keeping up with the existing nuclear capacity would deplete the high grade ores so that by 2016, the mean uranium ore grade available would reach 0.1 percent or less. And at some time between 2066 and 2076, when average ore grade decreases to 0.02 percent or less, uranium fuel reactors would fall off the 'energy cliff' i.e., consume more energy than they generate, and produce more CO_2 emissions than a gas-fired power plant.

The solution is obvious. We must give up nuclear energy once and for all. "Nothing can be implemented faster than the expansion of renewable energies," Hermann Scheer points out [9]. "Highly-centralized conventional power stations can be replaced by many smaller and mid-sized generation plants. A solar or wind-driven generator can be installed within a few days, while a nuclear power plant takes an average of 10 years to build."

8

BEWARE THE BIOCHAR INITIATIVE

Turning bioenergy crops into buried charcoal to sequester carbon won't work and could plunge the earth into an oxygen crisis towards mass extinction

Deadwood ecosystem by Mae-Wan Ho

STORY OF BIOCHAR UNRAVELS

The story goes that charcoal buried in the soil is stable for thousands if not hundreds of thousands of years and increases crop yields. The proposal to grow crops on hundreds of millions of hectares to be turned into buried 'biochar' is therefore widely seen as a "carbon negative" initiative that could save the climate and boost food production.

That story is fast unravelling. Biochar is not what it is hyped up to be, and implementing the biochar initiative could be dangerous, basically because saving the climate turns out to be not just about curbing the rise of CO_2 in the atmosphere that can be achieved by burying carbon in the soil, it is also about keeping oxygen (O_2) levels up. Keeping O_2 levels up is what only green plants on land and phytoplankton at sea can do, by splitting water to regenerate O_2 while fixing CO_2 to feed the rest of the biosphere [1].

Climate scientists have only discovered within the past decade that O_2 is depleting faster than the rise in CO_2, both on land and in the sea [2, 3]. Furthermore, the acceleration of deforestation spurred by the biofuels boom since 2003 appears to coincide with a substantial steepening of the O_2 decline. Turning trees into charcoal in a hurry could be the surest way to precipitate an oxygen crisis from which we may never recover.

BURYING CHARCOAL TO SAVE THE CLIMATE

The International Biochar Initiative (IBI), according to its website [4], was formed in July 2006 at a side meeting of the World Soil Science Congress at Philadelphia, Pennsylvania, in the United States, by people from academic institutions, commercial ventures, investment banks, non-government organizations and federal agencies around the world, dedicated to research, development, demonstration, deployment, and commercialisation of biochar on a global scale.

IBI has introduced biochar into the 2008 US Farm Bill, so it now counts among a handful of "new, high-priority research and extension areas". IBI is also working with the United Nations Convention to Combat Desertification to promote biochar in the post-Kyoto climate agreement. And the United Nations Framework Convention on Climate Change has already included biochar in a section entitled: "Enhanced Action on Mitigation" to serve as basis for negotiations during pre-Copenhagen meetings [5].

Biochar is just charcoal, produced by burning organic matter such as wood, grasses, crop residues and manure, under conditions of low oxygen (pyrolysis). A number of different pyrolysis techniques exist depending on temperature, speed of heating, and oxygen delivery [6, 7], resulting in different yields of biochar and co-products, "bio-oil" (with energy content value approx 55 percent that of diesel fuel by volume) and "syn-gas" (a mixture of hydrogen, carbon dioxide, carbon monoxide, and hydrocarbons), which can be used to generate electricity, or as low-grade fuel for ships, boilers, aluminium smelters and cooking stoves.

IBI has encountered strong criticism as a "new threat to people, land and ecosystem" in a declaration signed by more than 155 non-profit organisations worldwide [8]. But patent applications have been made, and companies formed for commercial exploitation of biochar production. Intense lobbying is taking place for biochar to be included in the Kyoto Protocol's Clean Development Mechanism for mitigating climate change [9, 10], so people implementing that technology would be able to sell certified emission reduction (CER) credits.

Things have moved forward so fast with so little public awareness and debate that critics are alarmed, especially over the proposal from some prominent advocates that 500 million hectares or more of 'spare land' could be used to grow crops for producing biochar [11, 12], Most of this would be found in developing countries; just as was proposed in the biofuels initiative several years earlier.

Figure 8.1 Terra preta left compared with surrounding soil right

BIOFUELS PROVING DISASTROUS

The biofuels boom has already exacerbated climate change by speeding up deforestation and peatland destruction, loss of habitats and biodiversity, depletion of water and soil, and increased use of agro-chemicals. Above all, it has generated poverty, land grabs, land conflicts, human rights abuses, labour abuses, starvation and food insecurity as documented by BiofuelsWatch and 10 other groups [13, 14] (see also [15]. Calls for a moratorium on biofuels came from Africa, the US, and the United Nations [16].

Biofuel production - mainly bioethanol and biodiesel - more than doubled between 2003 and 2008, driven by rising oil prices; while food prices rose 70 percent between 2005 and 2008 [17], according to data compiled by the International Monetary Fund. The UN declared 2008 the year of the Global Food Crisis [18]; food riots and fuel protests were rife. UK's Environment Audit Committee joined the call for moratorium in January 2008 [19], and reiterated it in May 2008 [20].

Biochar is widely seen as the successor to biofuels on grounds that it will sequester carbon and improve soil fertility while also producing energy. According to its proponents, biochar is not just carbon neutral; it is "carbon negative", according to its proponents, because buried biochar is stable for thousands, if not hundreds of thousands of years.

A lifecycle analysis published in 2008 [21] by John Gaunt and Johannes Lehmann, leading biochar proponent at Cornell University, New York, in the United States, considered both purpose grown bioenergy crops (BEC) and crop wastes (CW) as feedstock. The BEC scenario involves a change from growing winter wheat to miscanthus, switchgrass, and corn as bioenergy crops. The CW scenario considers both corn stover and winter wheat straw as feedstock. The energy balance is much more favourable than the production of biofuels such as ethanol from corn. The avoided emissions are between 2 and 5 times greater when biochar is applied to agricultural land than used solely for energy in fossil energy offsets. Some 41–64 percent of emission reductions are related to the retention of C in buried biochar (so the stability of biochar is important), the rest due to offsetting fossil fuel use for energy, fertilizer savings, and avoided soil emissions of N_2O and CH4, as additional effects of biochar. Unfortunately, the analysis is largely based on assumptions. Biochar is now found to be not quite as stable as claimed and can speed up litter decomposition in the soil (see below). The energy balance of pyrolysis is taken as that reported by one company; and there is lack of conclusive evidence in support of the supposed significant N_2O reduction for at least ten years [6, 11].

BIOCHAR IS NOT 'TERRA PRETA'

The biochar initiative was inspired by the discovery of 'terra preta' (black earth) in the Amazon basin [22, 23], at sites of pre-Columbian settlements (between 450BC and 950AD), made by adding charcoal, bone, and manure to the soil over many, many years (see Fig. 8.1). Besides charcoal, it contains abundant pottery shards, plant residues, animal faeces, fish and animal bones. The soil's depth can reach 2 metres, and is reported capable of regenerating itself at the rate of about 1 cm a year. Similar sites are found in Benin and Liberia in West Africa, in the South African savannahs, and even in Roman Britain. According to local farmers in the Amazon, productivity on the terra preta is much higher than on surrounding soils.

Investigations in the laboratory revealed that terra preta soils are rich in nutrients such as nitrogen, phosphorus, calcium, zinc, and manganese, and have high levels of microbial activity. Terra preta contains up to 70 times more black carbon (BC) than the surrounding soils. Due to its polycyclic aromatic structure, black carbon is believed to be chemically and microbiologically inert (but see later) and persists in the soil for centuries, if not thousands of years. During this time, oxidation produces carboxylic groups increasing its nutrient-holding capacity. Bruno Glaser and colleagues at the University of Bayreuth concluded that [23] "black carbon can act as a significant carbon sink and is a key factor for sustainable and fertile soils, especially in the humid tropics."

Similarly, BC derived from terra preta sites in central Amazon differing in age from 600 to 8 700 years were chemically, biologically and spectroscopically indistinguishable, as consistent with their "extremely slow" rate of decomposition [24].

A ten-year trial in Swedish forests showed that buried charcoal appear to promote the breakdown of humus, thus completely offsetting the carbon sequestered in the charcoal

However, BC collected from 11 historical charcoal blast furnace sites from Quebec Canada to Georgia USA, were quite different from BC newly produced using rebuilt historical kilns [25]. The historical BC samples were substantially oxidized after 130 years in soils compared to the new BC, or new BC incubated for one year at 30˚C or 70˚C. The major alterations were an increase in oxygen from 7.2 percent in new BC to 24.8 percent in historical BC; a decrease in carbon from 90.8 percent to 70.5 percent; formation of oxygen-containing function groups, particularly carboxylic acid and phenolic functional groups; and disappearance of surface positive charge, to be replaced entirely by negative charges. New BC incubated at 30˚C or 70˚C for 12 months increased in oxygen concentrations to 9.2 and 10.6 percent respectively; and also had complete replacement of surface positive charges by negative charges.

These findings show that BC is a substantial oxygen sink, and could deplete atmospheric O_2 fairly rapidly if massive amounts are produced in a hurry!

The main factor accounting for the changes was mean annual temperature, which was highly correlated with degree of oxidation. BC oxidation was increased by 87 nmoles/kg˚C / degree Celsius increase in mean annual temperature. BC oxidation to carboxylic groups accounts for the high cation exchange capacity of natural BC in the soil that the authors suggest is the basis of the enhancement in soil fertility.

So charcoal is *not* the same as terra preta that has been created over thousands of years by human intervention and natural geochemistry. The claim that biochar is a "stable carbon pool" in the soil that does not degrade for thousands of years is not borne out by the study, nor by a number of other studies (see below).

Naturally occurring black carbon has a far more complex relationship with the soil and the earth as a whole, as recent research is revealing. Moreover, black carbon pollution from fossil fuel and biomass burning associated with deforestation contribute as much to global warming as CO_2, and climate scientist are proposing a reduction of black carbon emissions as a way of cooling the planet [27]. That's another reason the biochar initiative will spoil the climate, by increasing BC emissions.

BIOCHAR INCREASES LOSS OF ORGANIC CARBON

A ten-year trial in Swedish forests showed that buried charcoal appear to promote the breakdown of humus, the decomposing plant matter on the forest floor [27], thus completely offsetting the carbon sequestered in the charcoal.

David Wardle and colleagues at Umeå University started their experiment to investigate the effect of forest fires on soil ecology. They buried hundreds of litter bags containing humus, charcoal, or a 50–50 mixture of the two in several sites in the Swedish boreal forest.

Periodically, they weighed the bags and measured the concentration of carbon and nitrogen. After just one year, they began to see an unexpectedly large decrease in mass from the bags containing the humus–charcoal mixture: 17 percent (the expected was 9 percent), compared to 18 percent in the bags with only humus and 2.5 percent in the bags with only charcoal Over ten years, the bags with mixed humus and charcoal released just as much carbon as did those containing only humus (130 mg per g initial mass), instead of only half as much as would be expected if charcoal had no effect on the loss of carbon from humus. The bags with charcoal had lost a small amount of their carbon (less than 5 mg per g initial mass) but gained about the same in nitrogen and microbial activity. The mixture did not gain or lose any nitrogen while humus released 2 mg N per g initial mass.

The results show that burying charcoal can speed up the decomposition of forest humus during the first decade, thus offsetting nearly all of the carbon sequestered in the charcoal itself.

BIOCHAR NOT A STABLE CARBON POOL

Caroline Masiello, marine chemist at Rice University Houston, Texas, in the United States, pointed to an apparent discrepancy in the production and deposition of of BC on both sea sediment and on land [28]. BC production globally was previously estimated at 0.05 to 0.27 Gt/y [29], representing 1.4 to 1.7 percent carbon exposed to fire that's converted to BC. The only documented loss process for BC is deposition in ocean sediments. However, the rate of total organic carbon deposited on the seafloor is only 0.16 Gt/y. Even assuming the lower end of the BC production rate, 0.05 Gt/y, would mean that BC should be 30 percent of ocean sediment organic carbon; but the actual measured amount is 3-10 percent.

Furthermore, isotope studies of highly refractory BC detected 14C graphite BC in sediment from the Northeast Pacific coastal transept. This was not a product of fossil fuel combustion but the result of erosion of very old graphite from rocks and deposited into the ocean, partly petrogenic. If BC deposited in ocean sediments comes both from biomass burning and from recycled petrogenic graphite, even less of the annually produced BC can be accounted for in ocean sediments. So where does the rest of the earth's annually produced BC go?

The same applies to BC on land. If BC has been produced since the last glacial maximum from biomass burning at the same rate as it is now produced, and if it is as stable as assume, it should account for 25 – 125 percent of total soil organic carbon pool. Instead, only a few measurements of BC or soil organic carbon ever reach 25 percent. A study of BC production during Siberian boreal forest fires made clear that not enough BC remains even after 250 years to account for all the BC produced during a fire [30] - estimated at 0.7 -0.8 percent of organic carbon - due to a combination of *in situ* erosion and translocation within the soil profile, with *in situ* degradation being the most likely.

In a later study, the amount of BC in organic carbon was compared in soils of three Siberian Scotch pine forests with frequent, moderately frequent, and infrequent fires [31]. The researchers concluded that BC did not significantly contribute to the storage of organic matter, most likely because it is consumed by intense fires. They found 99 percent of BC in the organic layer, with a maximum stock of 72 g/m^2. Less intense fires consumed only parts of the organic layer and converted some organic matter to BC, whereas more intense fires consumed almost the entire organic layer.

But appreciable degradation of BC can also occur in the absence of fires, by microbial action or photo-degradation. The stability of BC was investigated in a sandy savannah soil at Matopos in Zimbabwe, where some soil plots have been protected from fire for the past 50 years [32]. The abundance of BC in these plots was compared to plots that have continued to be burnt. The plots protected from fire had 2.0+5 mg/cm^2 BC, about half of the 3.8+0.5 mg/cm2 found in plots burnt every 1-5 years. The half-life of BC at a depth of 0-5 cm of the soil protected from fire was estimated at < 100 years, and that of large particles <50 years. The results suggest that in well-aerated tropical soil environments, charcoal and other BC can be significantly degraded in a matter of decades.

BC is best understood as a continuum of combustion products, ranging from slightly charred, degradable biomass to highly condensed refractory soot [27]. All components of this continuum are high in carbon content, chemically heterogeneous and dominated by aromatic structures. The reactivity of BC also varies along the combustion continuum. Charcoal decomposes much more rapidly than soot when exposed to chemical oxidants, such as acid dichromate, in the lab [32].

The results are also complicated by the different ways of producing charcoal and different methods of quantifying BC [27]. In studies on the National Institute of Standards and Technology reference materials, the values varied by a factor of as much as 500, depending only on the method used in quantification.

Research in the atmospheric chemistry community has shown that even soot, the most inert part of the combustion spectrum, can be chemically altered on a very short timescale through reaction with atmospheric oxidants. Reaction with ozone and other atmospheric oxidants create hydrophilic carboxylic acid groups on its exterior These reactions are so rapid that solubilisation of soot particles can occur in 30 min in the presence of 50 ppb (parts per billion) ozone, making it possible to dissolve soot in a solution of distilled water. The ozone concentration in rural air in the US ranges diurnally from 20 to 70 ppb. So soot can enter some of the Earth's dissolved organic carbon pools.

BC has been measured by thermal techniques to be 5 to 12 percent of dissolved organic carbon in Chesapeake Bay, the Delaware Bay, and the adjacent Atlantic Margin. Another electrospray ionization with high resolution mass spectrometry applied to dissolved organic matter from a small stream in New Jersey and Rio Negro detected BC degradation products that were assigned chemical structures.

The results suggest that in well-aerated tropical soil environments, charcoal and other BC can be significantly degraded in a matter of decades

BIOCHAR& SOIL FERTILITY UNCLEAR

Experiments carried out so far have yielded equivocal results on the ability of biochar to increase productivity. There have been positive effects claimed, at least in the short term, but also some negative impacts, at least partly due to nitrogen limitation [33]. In a small scale lab experiment, biochar appeared to increase nitrogen fixation by legumes, principally by increasing the availability of trace elements boron (B) and molybdenum (Mo), and to a lesser extent, K, Ca, and P, while lowering N availability and Al saturation. The results on productivity were not statistically significant, however.

A report published in 2007 presented results on crop yields over four seasons [34]. Researchers at the University of Bayreuth in Germany, and EMBRAPA Amazonia Occidental Manaus in Brazil carried out a field trial near Manaus on cleared secondary forest with 15 different amendment combinations of chicken manure (CM), compost (CO), forest litter, chemical fertilizer (F), and charcoal (CC) applied once on rice and sorghum, and followed over four cropping cycles (see Fig. 8.2).

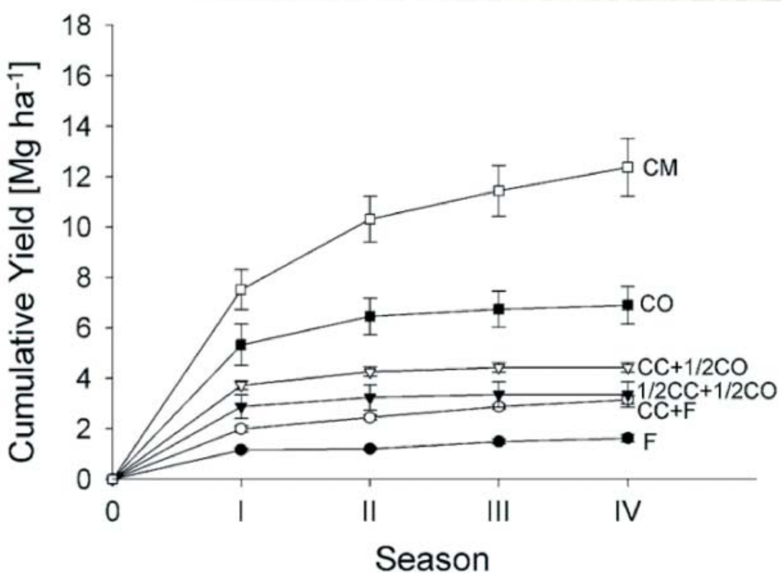


Figure 8.2 Biochar and crop yields in combination with other amendments

Chicken manure gave by far the highest yield over the four cycles (12.4 tonne/ha). Compost application came second at about half the yield, but was still four times higher than chemical fertilizer. The control, leaf litter (burnt and fresh), and charcoal treatments gave no grain yields after the second season, and were discontinued.

It is clear that biochar has not lived up to its promises as a stable C repository or enhancer of crop yields

In combination with compost, charcoal amendment decreased yield by about 40 percent compared to compost alone, and only improved yield in combination with chemical fertilizer. The charcoal was derived from secondary forest wood bought from a local distributor, and applied at the rate of 11 tonne/ha. This corresponded to the amount of charcoal C that could be produced by a single slash-and-char event in a typical secondary forest on the dry iron-rich soil of central Amazonia.

The highest yields for all treatments were obtained at the first harvest, and except for chicken manure, yields declined rather sharply by the second harvest.

A second fertilization with chemicals was applied after the second harvest to all remaining treatments, but that did not improve the yields.

Plants fertilized with chicken manure had the highest nutrient contents followed by plants that received compost and/or chemical fertilizer. Chicken manure significantly improved the K and P nutrition compared to all other treatments, while charcoal applications did not show a significant effect on nutrient levels. Most importantly, surface soil pH, phosphorus, calcium and magnesium were significantly enhanced by chicken manure. Plots fertilized by chicken manure had pH higher than 5.5 and increased cation exchange capacity.

These results are disappointing for those looking to promote 'biochar' as a means of improving the yield of crops at the same time as sequestering carbon, which also turns out to be illusory.

POTENTIAL FOR OXYGEN CRISIS REAL

It is clear that biochar has not lived up to its promises as a stable C repository or enhancer of crop yields. On the other hand, the risk of oxygen depletion is real [1-3]. Biochar itself is an oxygen sink in the course of degrading in the soil [24, 32]; adding to the depletion of oxygen that cannot be regenerated because trees have been turned into biochar for burial. And worse, as in the biofuels boom that has already apparently speeded up deforestation and oxygen depletion since 2003 [2], if biochar is promoted under the Clean Development Mechanism, it will almost certainly further accelerate deforestation and destruction of other natural ecosystems (identified as 'spare land') for planting biochar feedstock, and swing the oxygen downtrend that much closer towards mass extinction. This time round, it will be humans that go first.

9

CARBON CAPTURE & STORAGE

A FALSE SOLUTION

Too late to be of use, much too expensive, ineffective, and unsafe

WOVEN BRICKS by Kathy Haffegee

MEGA-PROJECTS COLLAPSE

Carbon capture and storage (CCS) is intended to reduce the impact of burning fossil fuels by capturing CO_2 from concentrated sources such as power stations and storing it underground (see Box 9.1). CCS has wide support among governments as the worlds oil supply is failing to meet demand while many countries still have large coal reserves.

Coal-fired power plants account for half of the US' electricity, and coal produces more carbon dioxide than any other commonly used fuel [1]. The coal-mining industry has been promoting CCS as "clean coal", and even some environmental groups see it as a way of bridging the energy gap until renewable energies can be more widely deployed.

The Bush administration was the first to commit to a large scale coal-fired power plant to be fitted with CCS, and intended as a flagship project for the world.

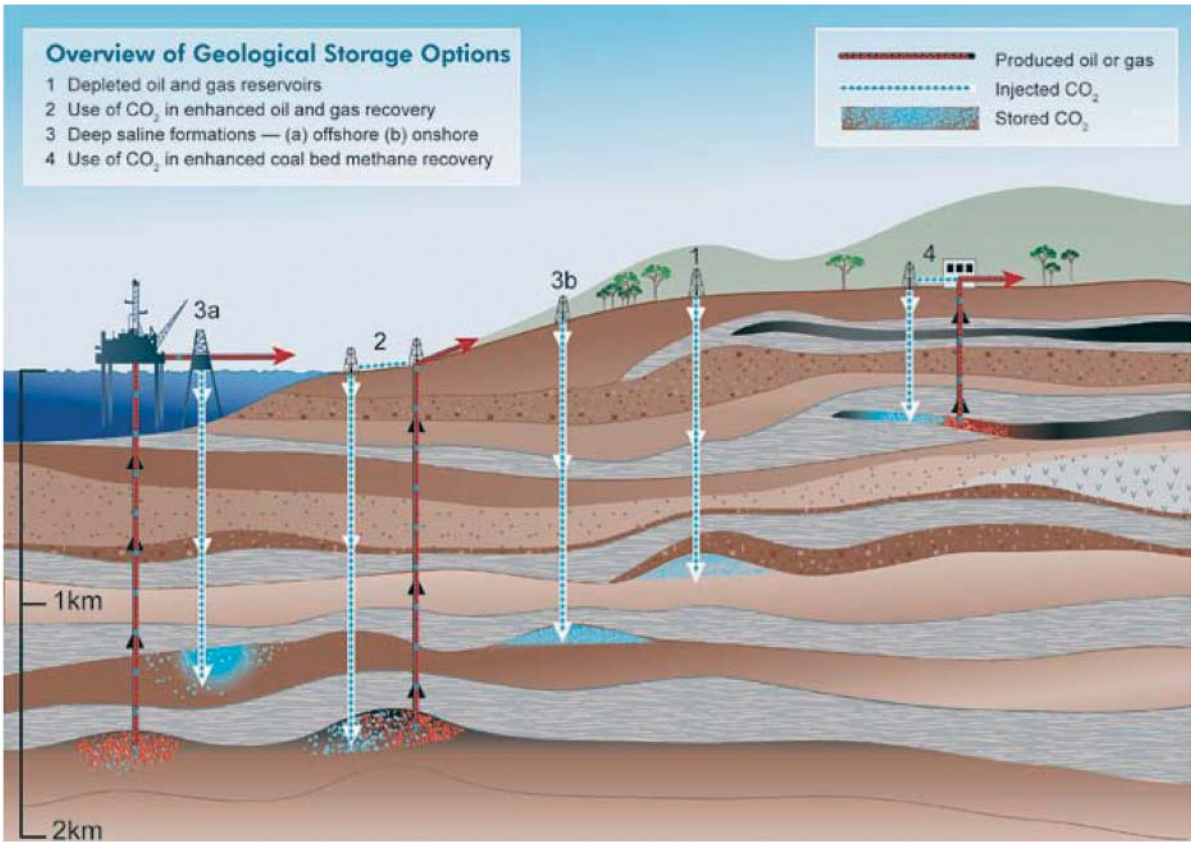
But on 30 January 2008, the US Department of Energy (DOE) withdrew support from the project, citing soaring cost and advances in electricity-generating technology in recent years [2, 3].

The non-profit public-private partnership FutureGen Alliance, which included industry giants such as Rio Tinto, American Electric Power Service Corp, Anglo American, BHP Billington, and China's largest coal-based power company, China Huaneng Group, was launched in 2005 in response to Bush's February 2003 call for a programme to demonstrate "the world's first near-zero-emissions coal-fired power plant.".

DOE described FutureGen in 2005 as a $950-million initiative for integrated gasification combined cycle (IGCC) technology to produce hydrogen and electricity while providing capture and storage of CO_2. At the time there were few IGCC projects. "Now, more than 33 IGCC projects have begun the permitting process," said Clay Sell, deputy energy secretary.

DOE first became aware that FutureGen's estimated budget for the plant to be built in Mattoon Illinois had almost doubled to $1.8 billion in March 2007; of which 74 percent would have to be paid by the DOE and the rest by industry. The consensus was that costs would only increase.

DOE intended to concentrate research on CCS, leaving IGCC to power developers. On the same day that it announced withdrawal from FutureGen, DOE issued a Request for Information from industry by 3 March 2008 on the costs and feasibility of building "clean coal" facilities that



Carbon storage options from IPPC report

achieve FutureGen's intended goals, so that by the end of the year, this should lead to a competitive tender for federal funding to equip clean coal plants of at least 300 MW with CCS technology.

FutureGen was not the only project to be abandoned. By the end of 2007, at least 11 CCS projects were scrapped in the UK, Canada and Norway [3]. Plans for new projects had stagnated, and the pace of development for existing projects slowed considerably.

In May 2008, Rio Tinto and UK oil producer BP dropped plans (through a subsidiary called Hydrogen Energy) to construct an Australian CCS coal-fired power generation plant Kwinana, admitting there was no guarantee that the rock formations at the intended site for carbon storage would seal it in [4]. The project would have cost AUS$1.5 billion to AUS$2 billion and captured around 4 million tonnes of CO_2 a year.

To put these CCS projects in perspective the world's total greenhouse gas emission is 28 Gt CO_2 equivalents a year and rising [5].

But these failures appeared to have done nothing to dampen the enthusiasm of governments or proponents for CCS. By May 2008, the US Senate Appropriations Committee unanimously approved a resolution to force the DOE to continue financing FutureGen out of the "war supplemental package" that includes funding for Iraq and Afghanistan wars as well as domestic spending on hurricane recovery, veterans education, food aid and federal highways [6].

In June 2008, the UK's Royal Society joined with science academies from other industrialised nations and five other countries including China and India to call on governments to set an agreed timetable for fitting power stations with CCS by next year to avoid "dangerous and irreversible" climate change [7].

In March 2009, US Energy Secretary Steven Chu said he wanted to have a fresh look at the FutureGen project and implement a modified version. As a result, Chu announced a contribution of an estimated $1.073 billion to the project in June 2009 [8], $1 billion of which was earmarked for carbon capture research. FutureGen's 20 member companies were expected to contribute a total of up to $600 million in additional non-federal funded, $200 million more than previously expected.

FALSE HOPES

There are grave doubts over the efficacy, economic viability, and safety of CCS, especially over its ability to meet the world's energy needs while mitigating climate change. As Greenpeace International's report [3], *False Hope, Why carbon capture and storage won't save the climate* charges, "the technology is largely unproven and will not be ready in time to save the climate."

It is clear that CCS as an integrated technological package will not be ready in time to counteract dangerous climate change. The earliest possible commercial deployment is not expected before 2030 [12]. The Intergovernmental Panel on Climate Change (IPPC) tells us that to avoid the worst impacts of climate change, global greenhouse gas (GHG) emissions have to peak by 2015 and start falling thereafter to 50 percent of 1990 levels by 2050. Its special report [9] does not see CCS to be commercially viable before the latter half of the present century; and even then, plants responsible for 40 to 70 percent of

Box 9.1

CARBON CAPTURE AND STORAGE

Carbon capture and storage involves the capture of CO_2 in a concentrated and compressed form that can be transported and pressure-injected underground for permanent storage at appropriate sites [3, 9].

CAPTURE

Capturing CO_2 is by far the most energy intensive part of CCS. Capture can be done by flue gas separation post-combustion, by 'oxyfuel combustion', or by pre-combustion separation. Pre- and post-combustion separation typically removes 85-95 percent of the CO_2, while oxy-fuel can remove up to 98 percent.

Flue gas separation is the standard practice and currently applied in about a dozen facilities worldwide. The flue gas is passed through a chemical solvent that absorbs CO_2. The CO_2 is recovered in a concentrated form and compressed for transport to the storage site, while the solvent is regenerated. The most commonly used CO_2 absorbent is monethanolamine (MEA). Newer methods are being developed that tethers the amine to silica [10] and may increase the efficiency of the process both in terms of CO_2 captured and energy use.

Oxy-fuel combustion depends on burning the fossil fuel in pure or enriched (95 percent) oxygen, so that the flue gas contains mostly CO_2 and H_2O, from which CO_2 can be removed easily. However, oxygen needs to be separated from nitrogen in the intake air, and this is costly. To date, this method has only been demonstrated at laboratory and pilot scale up to 3 MW.

Pre-combustion separation is usually applied in coal Integrated Gasification Combined Cycle (IGCC) power plants, and involves turning coal first into a mixture of CO (carbon monoxide) and H_2 (hydrogen). The CO is made to react with steam to generate more H_2 and CO_2, the latter is removed leaving H_2 for the turbine to generate electricity, or for hydrogen fuel cells to run vehicles. This method is not economical at the moment, and significant technical challenges remain.

TRANSPORT

Options for transport include pipelines, ships, rail and road, with pipelines the most likely. Transport by pipelines requires compression of the gas to a liquid state. Pipeline transport is currently used in the US, which has more than 2 500 km of CO_2 pipelines in the western half of the country where 50 Mt/y – an amount equivalent to the annual output of about sixteen 500 MW coal-fired power stations – is carried away for enhanced oil recovery (see below) projects in west Texas and elsewhere. No such infrastructure currently exists in Europe for moving CO_2 from power stations to storage sites.

STORAGE

Both ocean and geological storage sites have been proposed, which include subsequent monitoring and verification to ensure that the storage sites are intact, and the CO_2 does not escape.

Ocean storage involves injecting the CO_2 at great depths, preferably below 3 000 m, where the pressure is sufficient to compress CO_2 into a dense liquid that sinks to the sea bed to form CO_2 lakes. This option is seen as so risky that it is now generally discredited. It is not a permanent store, and the CO_2 will eventually dissolve and disperse into the overlying seawater, acidifying the oceans with drastic consequences on marine life. The oceans are already under great pressure from pollution, destructive over-fishing, increasing commercial exploitation and global warming; most worrying of all, they are failing to absorb the normal share of anthropogenic CO_2 released into the atmosphere [11]. Also, these storage sites are impossible to control or monitor, and are effectively prohibited by current international legislation [3].

Geological storage involves injecting the CO_2 into permanent rock formations sealed by dense impermeable rock layers more than 800 m below ground. Four options have received the greatest attention: deep saline aquifers, depleted oil and gas reservoirs, enhanced oil recovery and deep coal seams.

- Deep saline aquifers are porous rocks containing very salty water they provide an estimated storage capacity for 1 000 Gt CO_2, but safety and environmental protection are as yet undemonstrated.
- Depleted oil and gas reservoirs are probably the best characterised, and have the potential capacity of 675-900 Gt CO_2.
- Enhanced oil recovery (EOR) involves injecting CO_2 into existing oil and gas reservoirs to enhance extraction of oil. The best known project is in southeastern Saskatchewan, Canada, at the Weyburn Field. It uses waste CO_2 piped from a gasification plant in North Dakota. For every tonne of CO_2 injected, one tonne of oil is extracted. Over the 25 year lifespan of the project, it is expected that about 18 Mt of CO_2 will be injected into the ground to yield approximately 130 m barrels of oil. This option is most favoured by CCS advocates, but it has yet to prove feasible or economical on a large enough scale.
- Deep coal seams that cannot be mined can be used for adsorption of CO_2. In the process, methane is released that could be recovered and used to offset the costs of CCS. But a great deal of uncertainty remains over the technical aspects as well as the storage capacity.

electricity sector CO_2 emissions will not be suitable for carbon capture.

CCS wastes energy as it uses between 10 to 40 percent of the energy produced by a power station [9], thereby erasing the efficiency gains of the last 50 years and increasing resource consumption by one third [13]. Power stations with CCS not only require more energy, they will need 90 percent more freshwater than those without.

CCS is expensive, and could double the plant costs, resulting in an electricity price increase of 21 to 91 percent [3].

In Australia, CCS would lead, at best, to a 9 percent emissions reduction in 2030 and a cumulative reduction from 2005 to 2030 of only 2.4 percent, partly due to the lack of suitable carbon storage facility. In contrast, a modest improvement in energy efficiency at zero or negative cost could decrease emissions in 2030 by about the same amount, and cumulative emissions by twice as much.

The International Energy Agency describes a "capture-ready" plant as one "which can be retrofitted with CO_2 capture when the necessary regulatory or economic drivers are in place", which is so vague to make any station theoretically capture ready. In the UK, a new coal-fired power plant at Kingsnorth, Kent, is being sold as capture ready, but until then, it will pump out around 8 million tonnes of CO_2 per year, the total annual emissions of Ghana.

The IEA estimates that for CCS to deliver any meaningful climate mitigation effects by 2050, 6 000 projects each injecting a million tonnes of CO_2 per year into the ground would be required. It is not clear that it can be done, and whether there are enough storage sites close to the power plants, as transport of CO_2 over distances greater than 100 kilometres is likely to be prohibitively expensive.

FALSE SOLUTION

CCS is certainly not a solution for mitigating climate change. It prolongs our dependence on fossil fuels *and* accelerates the production of CO_2, massive amounts of which are 'stored' at our peril because of the constant threat of leakage and escape (see below). Most of all, CCS squanders ever dwindling resources that should be invested instead in renewable energies such as solar, wind, and biogas from anaerobic digestion of biological wastes, and in developing other much more promising, safer, and cost-effective options [14].

A study commissioned by the German federal government confirmed that compared with renewable energy options such as wind and solar, CCS will increase CO_2 emissions 10 to 40 fold and raise the cost of electricity by 100 percent [15] (see next chapter).

CCS IS VERY COSTLY

CCS is extremely expensive because the power plant has to be specially constructed with the necessary infrastructure for transport and for storing the carbon. Financial considerations have been the major factor responsible for the string of collapses in CCS projects around the world.

In June 2008, the executive at RWE Npower, a company hoping to build a big new coal-fired power station fitted with CCS at Tilbury on the Thames Estuary, expressed concerns over both the cost and the timescale. Mr. Chris Elston said such coal-fired stations "could easily double the cost of electricity", and furthermore, it could take 20 years before CCS can be deployed across Britain's coal-fired stations.

CCS wastes energy as it uses between 10 to 40 percent of the energy produced by a power station

One proposal to make CCS more economically attractive is 'enhanced oil recovery' (EOR) (see Box 9.1), injecting CO_2 into an underground reservoir to force out the remaining oil or gas, thereby increasing the amount that can be extracted and extending the life of the oil field up to 20 years. The British Miller oil and gas field became uneconomical in 2005, and oil giant BP sought government subsidies to initiate an EOR project that would allow access to an estimated 57 barrels of extra oil. But the potential profits from the recovered oil could not compensate for difference between the costs of CCS, estimated at €38 per tonne, and the price of carbon credits, then at €21 per tonne. BP tried to convince the UK government to bridge the gap with a tax break of over 50 percent, and a guaranteed subsidised rate of return. The UK government decided that all proposed CCS projects had to compete for funding and tax relief; and BP cancelled its plans [3].

The Norwegian government abandoned a similar project after the Statoil-Hydro and Shell companies withdrew on economic grounds.

The Norwegian government is, nevertheless, committed to covering all additional construction and operation costs to ensure CCS from two natural gas-fired power plants on the Norwegian west coast, Kårsto and Monstad. The Kårsto plant, which emits around 1 million tonnes of CO_2 a year, began operating in November 2007. High gas costs and low electricity returns meant it has hardly been functioning. Full scale CCS was promised from 2009, but is postponed to 2012 or beyond, due to significant technological constraints. The capture plant, pipeline to the storage location, and the control facility for the storage process have yet to be built. At the Mongstad refinery that was to be the "European CCS test centre", two pilot plants are under construction, with the aim of capturing 100 000 tonnes of CO_2 per year from 2011. Yet, until 2014 at the earliest, the captured CO_2 will simply be released back into the atmosphere because the pipelines to the storage sites will not be in place.

Before the last collapse of the now resuscitated FutureGen, its costs had ballooned to US$1.8 billion and threatening to increase.

DANGER OF CARBON LEAKAGE OR ESCAPE

As long as CO_2 is stored in geological sites, there is a risk of slow leakage or large scale escape that will impact the surrounding environment and negate the climate mitigating effect.

A natural example of the danger of CO_2 escape occurred at Lake Nyos Cameroon in 1986 following a volcanic eruption, which released large quantities of the CO_2 had accumulated at the bottom of the lake. It killed 1 700 people and thousands of cattle within a 25 km radius [3].

To be viable, the CO_2 captured and stored must leak at a globally averaged rate of not more than one percent a year over a timescale of centuries

A 2006 US Geological Survey pilot field experiment was carried out to test deep geological disposal of carbon dioxide in a saline sedimentary rock formation in Frio, Texas. The researchers found that the buried CO_2 dissolved large amounts of the minerals in the rocks responsible for keeping the gas contained [16]. The CO_2 dissolved in the salty water, turning it to acid. The acidified brine dissolved other minerals, including metals such as iron and manganese, organic material and relatively large amounts of carbonates that naturally seal pores and fractures in geological sites. Carbonate is also found in the cements used to seal abandoned oil and gas wells. Dissolving these carbonate seals could release CO_2 into the atmosphere. The contaminated brine could further leak into aquifers and contaminate drinking and irrigation water. The lead scientist in the field experiment Yousif Kharaka warned [3] that the results are "a cautionary note" that calls for "detailed and careful studies of injection sites" and for "a well thought out monitoring programme to detect early leaks of CO_2 into shallow potable groundwater or to the atmosphere." To be viable, the CO_2 captured and stored must leak at a globally averaged rate of not more than one percent a year over a timescale of centuries; otherwise, the emitted flux will be greater than or equal to that intended to be mitigated initially [17].

The environmental risks of geological CO_2 storage include [3]:

- Slow leakage from storage sites, for example, through geological faults
- Escape of CO_2 and associated substances into shallow groundwater
- Displacement and mobilization of toxic metals and organics upwards to contaminate potable water, overlying sediments, soils and seawater
- Escape of other hazardous captured flue gases.

Local escapes of CO_2 pose a threat of asphyxiation to humans and animals. CO_2 is denser than air and tends to accumulate in low-lying, poorly ventilated areas. It becomes a health hazard at levels greater than 3 percent, as demonstrated in Lake Nyos incident in Cameroon. CO_2 rising to the shallow subsurface can have lethal effects on plants and subsoil animals and contaminate groundwater. Soil acidification and suppression of root respiration has been reported in volcanic and earthquake zones. In Mammoth Mountain, California, the release of CO_2 following several small earthquakes was sufficient to kill a hundred acres of trees. Migration of CO_2 can acidify water and mobilize toxic heavy metals. Its injection underground can build pressure, displace brines and cause seismic activities. The increased extraction associated with CCS and more fossil fuel use also means greater environmental damage [14].

INDUSTRY WON'T TAKE RISK ON CCS

CCS is considered so risky on a large scale that industry is unwilling to fully invest in it without a framework that protects it from long-term liability [3]. Some utilities are unwilling to make CO_2 available for storage unless they are released of ownership upon transfer of the CO_2 off the property of the power station. Potential operators are ensuring that they only retain liability for permanently stored carbon for ten years.

FutureGen was not only promised unprecedented public funds to the tune of US$1.3 billion, it was also protected from financial and legal liability in the event of an unanticipated release of CO_2, and even had its insurance policies paid for.

PROFLIGATE FUNDING FOR CCS CONTINUES

CCS is diverting funds away from renewable energy options. The US DOE's 2009 spending on CCS is $623.5 million, a 26.4 percent increase over 2008, at the same time that it is scaling back programmes on renewable energy and efficiency by 27.1 percent to US$145.2 million [3].

Australia has three cooperative research centres for fossil fuels, one focussing on CCS; but there is not a single research centre for renewable energy technology. In Norway, petroleum-based research receives over five times more funding than renewable energy research; a gap further widened by a recent commitment of more than 20 billion NOK (US$4 billion) for two CCS projects aimed at capturing 2 MtC annually.

Meanwhile, the renewable energy market is booming. In 2007, global annual investment in renewables exceeded US$100 billion [3]. New Zealand plans to achieve carbon neutrality by mid-century. It already obtains 70 percent of its electricity from renewable resources and aims to increase it to 90 percent by 2025. Germany increased its use of renewable energies by 300 percent in the past ten years.

10

RENEWABLES *VS* CCS

CCS emits 10 to 40 times as much greenhouse gases as wind or solar and gives no protection against rising cost of fossil fuels

A study commissioned by the German federal government and led by researchers at the German Aerospace Center in Stuttgart compared carbon capture and storage (CCS) with renewable energy technologies using a combined lifecycle analysis and cost assessment for Germany [1].

CCS increases photo-oxidants (that damage DNA), eutrophication (that destroy aquatic life), acidification (that damage trees and other plant life), and toxicity to humans, all by about 40 percent

The results show that per kWh of electricity generated, CCS cuts CO_2 emissions by 72-90 percent, and total greenhouse gas emissions by 65-79 percent, assuming that the technology works as planned and the geologically stored CO_2 does not leak out at all; any leakage would compromise the mitigating potential of CCS.

However, the net emissions from CCS are still 10 to 40 times those from renewable energies such as solar and wind (see Figs. 10.1 and 10.2).

The difference between CO_2 and greenhouse gas emissions comes from the methane released when coal is mined; methane has a global warming potential about 20 times that of CO_2. If companies take steps to prevent the release of methane and capture it for use in combined heat and power generation plants, then the advantage gained is equivalent to fitting CCS for lignite power plants.

Assuming that CCS could be fitted to new Integrated Gasification Combined Cycle (IGCC) and Natural Gas Combined Cycle (NGCC) plants by 2020, electricity would end up costing roughly

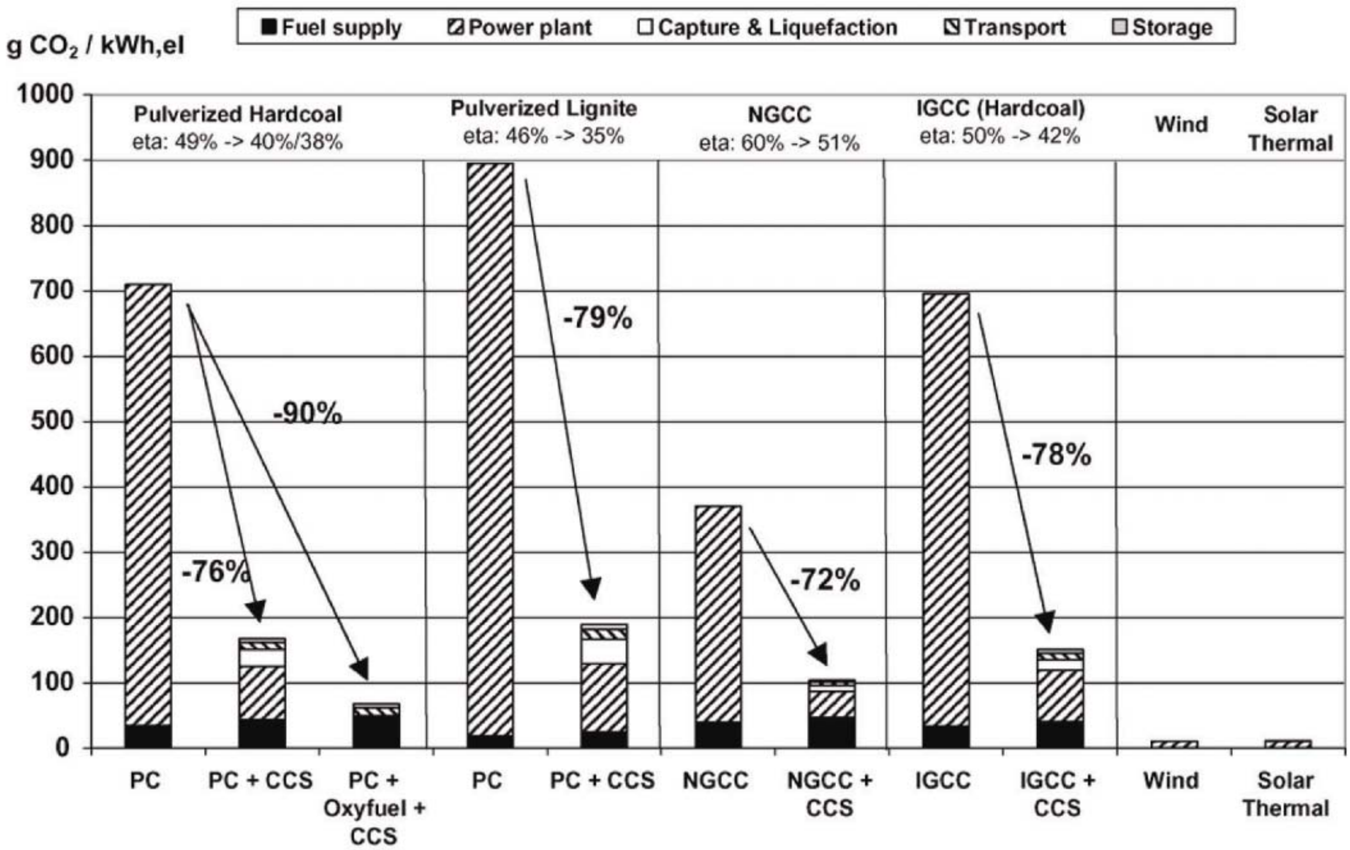


Figure 10.1 Carbon dioxide emissions for coal and natural gas power stations with and without CCS compared with renewable wind and solar

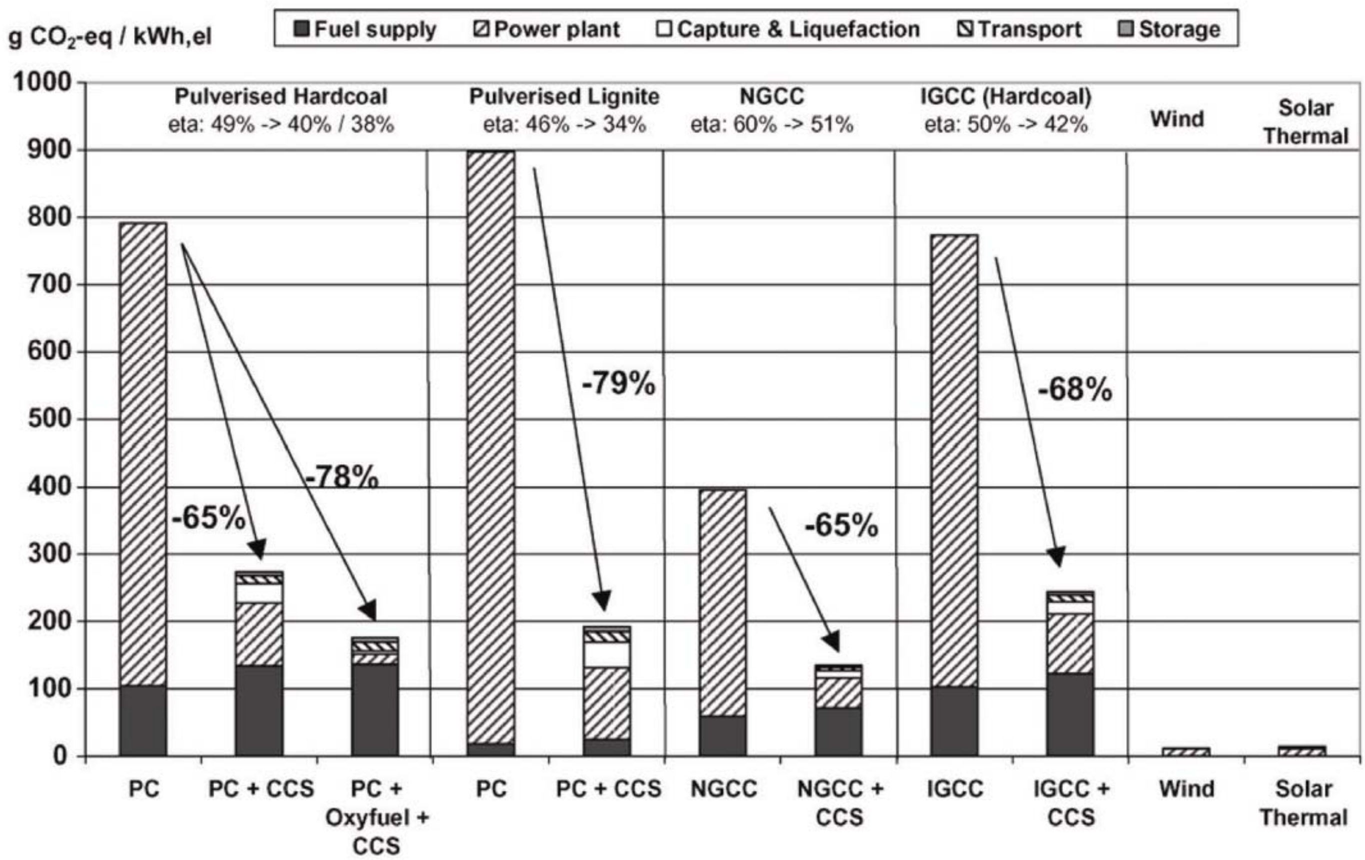


Figure 10.2 Greenhouse gas emissions for coal and natural gas power stations with and without CCS compared with renewable wind and solar

twice as much as without CCS. While renewables are currently more costly, the improvements in technology would bring the price of electricity from offshore wind plants for example to half the price of fossil fuel plants with CCS. The advantage of solar and wind energies is that they are immune from price increases of fossil fuels. They are also much less costly to install and therefore provide more flexibility in taking advantage of improvements in technology.

The assumption that the first commercially operated power plant with CCS will be operating by 2020 is built in to the study because Germany faces the problem that a large number of its fossil power plants are reaching the end of their life in the next 15 years. So, only if CCS technology can be retrofitted by 2020 would it stand a chance of delivering the climate protection goal of reducing any greenhouse gas emissions at all.

Unfortunately, CCS remains unproven as a technological package. The earliest possible deployment is 2030 according to the World Business Council for Sustainable Development, while the Intergovernmental Panel for Climate Change does not expect CCS to be commercially viable before the second half of the present century [2] (see previous chapter).

When further impacts are factored in [1] CCS increases photo-oxidants (that damage DNA), eutrophication (that destroy aquatic life), acidification (that damages trees and other plant life), and toxicity to humans, all by about 40 percent.


RENEWABLE & SUSTAINABLE NOW
POON

11

WORLD SHIFTING TO RENEWABLES *NOW*

100 PERCENT BY 2050

More renewable energies capacity added than conventional for the first time in 2008 and 100 percent predicted by mid-century

Pheonix 2 by Mae-Wan Ho

In 2008, for the first time, more renewable energy than conventional power capacity was added in both the European Union and United States, showing a [1] "fundamental transition of the world's energy markets towards renewable energy." This is the finding of the Renewables Global Status Report released by REN21 based in Paris [2], and confirmed by British Petroleum's Statistical Review [3], and the World Council for Renewable Energy [4].

Global power capacity from new renewable energies (excluding large hydro) reached at least 280 GW in 2008, a 16 percent rise from the 240 GW in 2007, and nearly three times the capacity of the US nuclear sector. New renewable energies now account for 6.2 percent of the global formal power sector capacity. This does not include, for example, the rapidly growing household generation of biogas in China, estimated to have reached 9 GW at the end of 2008 (see Chapter 20); and is in addition to the traditional renewable of large hydroelectric that accounts for 6 percent, and fuel wood and other biomass in poor households, estimated at 12 percent.

The global shift to renewables has come in the midst of an historic and global economic crisis, Mohamed El-Ashry, Chair of REN21 points out.

At least 73 countries have renewable energy policy targets today, up from 66 at the end of 2007.

SOLAR

Solar tops the list of renewable energies, beating wind power. Solar heating capacity increased by 15 percent to 145 GW (Chapter 12 gives 147 GW). Solar hot water in Germany set record growth in 2008, with over 200,000 systems installed taking its total capacity to 7.3 GW [5]. Grid-connected solar photovoltaic power continued to be the fastest growing power generation technology, with a 70 percent increase in existing capacity to reach 13.4 GW. Growth has averaged 42 percent a year over the past 10 years, doubling every two years. Growth was highly concentrated in 2008. Spain, the solar photovoltaic market leader, with 2.7 GW of new grid-tied installations and Germany, with 1.5 GW, together account for more than 75 percent of the 5.5 GW increase, due to strong government support. The concentrating solar power industry saw many new entrants and new manufacturing facilities in 2008, and currently accounts for 0.469 GW (see Chapter 12).

WIND

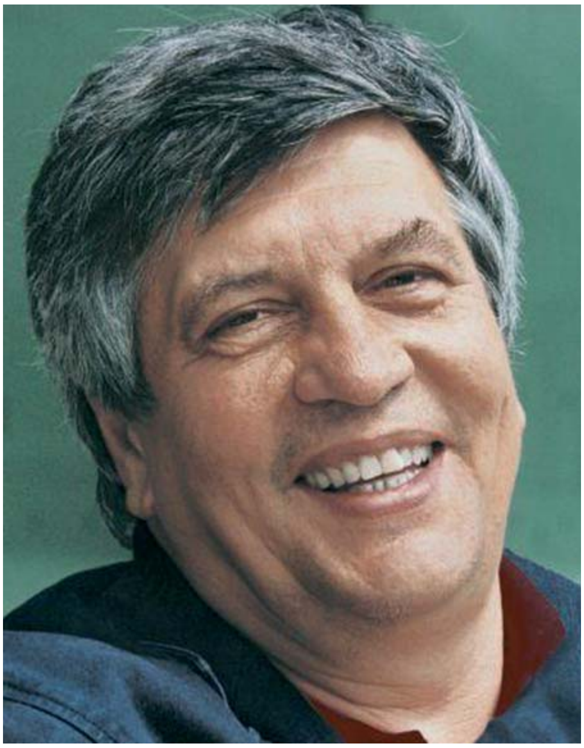
Global wind power capacity grew by 28 GW in 2008 to reach 122 GW. This was the fifth consecutive year of accelerating growth of just over 28 percent per annum. The US and China led the growth. The US led by 8.4 GW, a 49.5 percent increase on 2007; while China recorded the fastest growth rate and the second highest capacity increment at 6.2 GW. China's total wind power capacity doubled in 2008 for the fifth year running. The US now has the largest wind power capacity at 25.2 GW (20.7 percent of world total) having overtaken Germany's 23.9 GW (19.6 percent of total).

Led by Germany and Spain, Europe has a total capacity of 66 GW, or 54 percent of total. Non-OECD generation capacity has doubled since 2002 and reached 22 percent in 2008, the growth led by China and India with a combined capacity of 8 GW or 85 percent of new non-OECD capacity.

Wind power generated electricity is a significant share for some countries: around 20 percent in Denmark, 11 percent in Spain and 7 percent in Germany.

GEOTHERMAL

Geothermal was the slowest growing renewable, its capacity reached 10.4 GW in 2008, led by the United States. The US has the largest geothermal



Hermann Scheer

capacity now at 3 GW (28.6 percent world total) followed by the Philippines at 2 GW, Mexico and Indonesia at 1 GW each. Geothermal energy is well established and relatively mature form of commercial renewable energy. It has a high load factor (output power versus maximum rated capacity) of 90 percent, compared to about 20 percent for solar and 25 percent for wind. Direct geothermal energy delivered by ground source heat pumps is now used in at least 76 countries.

New renewable energies now account for 6.2 percent of the global formal power sector capacity

SMALL HYDRO

Global small-scale hydroelectric power is estimated at about 100 GW [4]; with 20 GW new in 2007, and 12 GW within the European Union (EU).

BIO-POWER

Bio-power includes biomass, biofuels and biogas. Biofuels such as ethanol and biodiesel from food crops, though renewable are not sustainable (see Chapter 7). They compete with food for feedstock, raising food prices and increasing hunger and poverty. They have accelerated deforestation and destruction of other natural ecosystems; and instigated land grabs and forced eviction of indigenous communities. Global fuel ethanol grew 31 percent to 35 Mtoe (tonnes of oil equivalent) in 2008, with growth accelerating for the fourth year in a row, led by the expansion in the US. Production grew by 41 percent to 17 Mtoe in the US, which now produces half of world fuel ethanol. The US and Brazil together now produce nearly 90 percent of global supply. Brazil's production rose by 20 percent to 14 Mtoe. Elsewhere, production rose by 30 percent led by increases in Canada and France.

Biogas is generated by anaerobic digestion, traditionally from agricultural and other organic wastes, and is highly sustainable as it also prevents greenhouse gas emissions, and environmental pollution, conserves nutrients, and produces rich fertilizer and soil conditioner as by-product (see Chapter 20). But increasingly, biogas is also produced from food crops (Chapter 21), and that is not sustainable. At the end of 2008, global bio-methane power reached 18.5 GW [4], while total bio-power – including an increasing trend towards small co-generation units for heat and electricity, two thirds of which are in the EU - is estimated at about 50 GW.

New investment in renewables reached $214 billion, up 44.6 percent from $148 billion in 2007

EMERGING MARKETS

China and India are increasingly playing major roles in both the manufacture and installation of renewable energy. India emerged in 2008 as a major producer of solar photovoltaics, with new policies leading to US$18 billion in new manufacturing investment plans or proposals.

New investment in renewables reached $214 billion [4], up 44.6 percent from $148 billion in 2007 [6], but down from the growth in the previous two years of over 50 percent. This was attributed to the impact of the financial crisis, which made investment fall by 53 percent in the first quarter of 2009 compared with the same period of 2008. There were signs of recovery in the second quarter of 2009, and stimulus packages are particularly important in nurturing this emerging market.

RENEWABLE TARGETS SET

Among the many new renewable energy targets set in 2008 [2], Australia targeted 45 TWh of electricity by 2020. Brazil's is seeking to slightly increase through 2030 its existing share of primary energy from renewable energy (46 percent in 2007), and its electricity share (87 percent in 2007).

India increased its target to 14 GW of new renewables capacity by 2012.

Japan set new targets for 14 GW of solar photovoltaic capacity by 2020 and 53 GW by 2030.

The EU formally adopted its target to reach a 20 percent share of renewable energy in final consumption by 2020, setting also country-specific targets for all member states.

The German Renewable Energy Act provided the major boost for the renewable energy industry, creating more than 150 000 new jobs and triggering annual renewable energy growth rates of 30 percent. Brazil and China have recently adopted similar policies

Obama, in his January 2009 speech, projected a doubling of renewable energy share of 9 percent within 3 years, with creation of 500 000 new jobs, improving the energy efficiency in 2 million homes and modernising 75 percent of federal buildings [4]. Over the next ten years, within the $798 billion stimulus package, there will be the following support for renewable energies: $2 billion a year for manufacturing tax credits, $8 billion in loans a year for power generation, and $2 billion a year for research, development, demonstration and deployment. In January, the German government trumped the world by setting a target of 50 percent renewable by 2050, and even 100 percent renewable may be on the cards (see Chapter 2). In June, China equalled EU with a target of 20 percent renewable by 2020 [7]. The UK pledges 30 percent of its electricity from renewable by 2020 (see Chapter 1); and Australia 20 percent of its electricity from renewable by 2020 [8].

Feed-in tariffs were adopted at the national level in at least five countries for the first time in 2008 and early 2009, including Kenya, the Philippines, Poland, South Africa, and Ukraine [2].

The REN21 report also shows that several hundred cities and local governments around the world are planning or implementing renewable energy policies and frameworks linked to carbon dioxide emissions reduction.

100 PERCENT RENEWABLES BY 2050

The World Energy Council representing the energy industry with members in over 90 countries [9] sees the global need for energy doubling by 2050, while the contribution of electricity increases by three fold. Shell projects a scenario with 65 percent renewable energy contribution to global consumption by 2060.

But many politicians and renewable energy experts in Europe, including the World Council for Renewable Energy see a realistic option of 100 percent renewable energy supply in a commercial market free of any subsidy by 2050 [4].

The World Council for Renewable Energy is chaired by Hermann Scheer [10], an economist by training, Social Democrat member of the German Parliament since 1980, President of Eurosolar (European Association for Renewable Energy), and recipient of the Right Livelihood Award in 1999 for his "indefatigable work for the promotion of solar energy worldwide."

Scheer's most successful policy innovations that have been implemented include the world's first 100 000 PV solar roof programme, the German Renewable Energy Act that resulted in 16 000 MW of decentralized renewable energy capacity installed, each at 5 MW or less (including 14 000 MW wind energy capacity), and full tax exemption for all biofuels, thereby decreasing their price below fossil fuels.

The German Renewable Energy Act provided the major boost for the renewable energy industry, creating more than 150 000 new jobs and triggering annual renewable energy growth rates of 30 percent. Brazil and China have recently adopted similar policies. As a result, China has the world's biggest solar PV industry, it has the world's largest park of installed solar water heaters, the highest growth rate of wind power installation in the world and it leads the world in the small hydro market [4].

ENERGY AUTONOMY IS THE KEY

Scheer's most important book, *Energy Autonomy: The Economic, Social & Technological Case for Renewable Energy* [11] argues that continued dependence on fossil fuels is dangerous because it relies on the world's politically most unstable region, the Middle East, exacerbated by peak oil, growing scarcity and mounting prices, and because of accelerating climate change.

The solution is to make the transition to renewable, distributed, decentralized energy generation, a model that has proven so successful in Germany itself.

Energy Autonomy is precisely what truly renewable and sustainable green energies offer. It is available where it is consumed, independent of any supplier, or on depleting resources and politically unstable energy producing regions of the world. It also ends the energy monopolies of conventional power industries such as nuclear and coal.

Renewable energies must be accompanied by political decentralization and promotion schemes instead of international top-down approaches that cannot recognize their local nature and regional particularities. There should be open and wide investments by many new players in the technological, financial and private field, stimulated by programmes like the German Renewable Energy Law instead of conventional government programmes involving half-committed and heavily subsidised conventional energy companies. Renewable energies involve a diversity of technologies and diverse regional implementations instead of market harmonization towards the most competitive renewable energy technology at present. Finally, renewable energies reflect taking ecological responsibility instead of only calculating monetary costs, and being indifferent towards the environmental benefits.

Wolfgang Palz of World Council for Renewable Energy remarks [4]: " Energy autonomy through renewable energy is a realistic option for all: communities, regions, nations. But as conditions of use are not the same everywhere, trade is important." As an example, the international trade of PV modules already exceeded US$ 15 billion in 2009. Trade in renewable energy stimulates peace, he says, while the fight for access to the fossil resources provokes military intervention. True, but trade alone will be unable to address the energy inequalities in the world. We need dedicated technology exchange and gifting to poor deprived countries in order to fulfil the ideals of a true energy autonomy for the world.

Energy Autonomy is precisely what truly renewable and sustainable green energies offer. It is available where it is consumed, independent of any supplier, or on depleting resources and politically unstable energy producing regions of the world. It also ends the energy monopolies of conventional power industries such as nuclear and coal

12

WHICH RENEWABLES?

Life cycle assessments reveal how much we can reduce greenhouse emissions and save on energy with different renewable options

Chewa mask Malawi

ELECTRICITY A MAJOR POLLUTER

The electricity industry currently contributes about 37 percent of the world's carbon emissions, predominantly from burning fossil fuels [1]. The best option for reducing carbon emissions is to substitute renewable energy resources for fossil fuels. Our recent report [2] *Food Futures Now* shows how a radical change in the way we produce and distribute food as well as energy can indeed free us from fossil fuels altogether.

Renewable energies such as solar and wind do not emit carbon dioxide while generating electricity, and have the further advantage of improving the efficiency of energy use considerably. Big power plants are located far away from most users, so the electricity generated has to be transported long distances over power lines where more than 7 percent may be lost before it is used. In addition, some 60-70 percent of the energy is lost as 'waste' heat while generating electricity. In contrast, solar panels and wind turbines are readily installed on or near homes and farms and the electricity generated as well as the heat can be consumed directly without much loss. Furthermore, because the capital costs of installation are much lower, they can be easily be upgraded to take advantage of technological improvements.

The electricity industry currently contributes about 37 percent of the world's carbon emissions, predominantly from burning fossil fuels

'CRADLE-TO-GRAVE' ASSESSMENT

A 'cradle-to-grave' life-cycle assessment (LCA) (see Chapter 6) is one that includes upstream processes such as mining, refining, transport, plant construction, the production of the device or equipment, the generation and distribution of electricity, and downstream processes such as decommissioning and disposal of wastes. This gives us a clearer idea as to how much better off we are with renewable electricity generation, and how different renewable options compare with one another.

In LCA, the main environmental performance indicators are as follows [3].

Energy intensity η, is the ratio of the total energy used for construction, operation and decommissioning E, to the electricity output of the plant/device over its lifetime E_t.

$$\eta = E/E_t \qquad (1)$$
$$E_t = P \times 8760 \text{ h/y} \times \lambda \times T$$

where P is the power rating, λ is the load factor (ratio of power output versus rated capacity) and T the lifetime. The inverse of energy intensity, the energy payback ratio (*EPR*), is considered one of the most reliable indicators according to the International Energy Agency. A high *EPR* indicates good environmental performance. An *EPR* of 1 or less indicates it consumes as much energy as it generates, so it should never be developed.

Energy payback time (*EPBT*) is the time it takes for the energy technology to generate the total energy requirement for construction, operation and decommission.

$$EPBT = E \times \varepsilon_{fossil} \times T / E_t \qquad (2)$$

where ε_{fossil} is the conversion efficiency.

Both *EPBT* and *EPR* tell us how much conventional energy we use today in order to obtain energy to-morrow.

Environmental impact (*EI*) assesses impact on the ecosystem. The general categories are acid rain potential, photochemical oxidants, global warming potential, etc. Other categories are impact on wildlife, loss of biodiversity, water quality, especially applicable to geothermal and marine energy technologies, including run-of-river hydro, tidal energy and wave energy, which still need to be carried out.

There are two major approaches to LCA: a process-based model developed mostly by the Society of Environmental Toxicology and Chemistry (SETAC) and the US Environment Protection Agency (EPA), and an economic input-output analysis referred to as EIO-LCA. The SETAC-EPA approach divides each product into individual process flows and identifies and quantifies *EI*s. This model includes all the various manufacturing, transport, mining and related requirements for making the product or service. The EIO-LCA traces out the various economic transactions, resource requirements, and environmental emissions required for a particular product or service. It uses sectors of the economy rather than specific processes, and also has difficulties analysing the use and disposal phases of certain products.

The renewable technologies for which most of the LCA work has been done are biomass, photovoltaic and wind energy. For example, the *EPBT* for onshore and offshore wind turbines in Denmark in 2000 were 0.26 and 0.39 y respectively, excluding glass and polyester because data did not exist, and about 94 percent of the materials of the wind turbine can be recycled. A study published in 2005 on 2.7kW PV systems found it consumed only 23 percent of the total primary energy of an oil-fired steam turbine plant, but its *EPBT* was a couple of months higher. The lifetime GHG emissions for the oil-fired steam turbine plant were about four times those of the PV systems. For biomass electricity, the LCA of wood-fired power plants in the range of 5 to 30 MW in Britain, the energy intensity is 0.25 to 0.27, and the CO_2 emission 65 g per kWh. A further analysis showed that an integrated biomass gasification combined cycle (IBGCC) power plant is superior to an integrated coal gasification combined cycle (IGCC) plant in terms of resource depletion and GHG emissions, whereas IGCC is better in terms of acidification and eutrophication.

LCA & ENVIRONMENTAL PERFORMANCE

Many factors contribute to environmental performance. The lifetime, power ratings, load factor (the output of a power plant compared to the maximum output it could produce), type and maturity of technology, country of manufacture, the type of material used, and method of decommissioning, all influence the energy intensity.

For example, in the case of a wind turbine, it is 0.049 for a steel tower and 0.041 for a concrete tower. The manufacture of a 500 kW German wind turbine in Brazil requires almost twice as much primary energy as one manufactured in Germany. And it is less energy intensive to recycle completely, or overhaul and reinstall after the service life is over than to recycle individual components.

Different LCA methodologies will also give different energy intensites for the same wind turbine. For example, the input output analysis gave higher energy intensity than process analysis because the former included more detailed information.

The environmental performance of PV technology differs in different countries. For Germany, the low irradiance reduces the *EPR*, but because it substitutes for a relatively dirty grid, CO_2 emission is reduced by 10.1 tonnes per kW of PV installed.

LCA FOR DIFFERENT SCENARIOS

LCA can be used to assess the environmental performance of alternative energy scenarios. It has been shown that the CO_2 emission per kWh for PVs can be reduced from 217 g to 68 with three improvements: in manufacturing technology, by changing the supporting structure to reduce aluminium use, and by increased efficiency of the solar cell. A study published in 1996 showed that the EPR could be increased from 2.4 to 6.7 using a 'solar breeding system' in which PV technology supplies electricity to produce further PV technology.

For bio-energy (biomass and biofuels), inorganic nitrogen fertilizer inputs have a strong influence on overall performance, accounting for 37 percent of non-renewable fossil energy input. Substituting for inorganic N fertilizer with sewage sludge 'bio-solids' could increase the EPR of willow biomass crop production by more than 40 percent.

This LCA does not include environmental impacts, which are substantial especially for coal-fired plants and big hydroelectric dams

LCA FOR DIFFERENT TECHNOLOGIES

A 2005 LCA showed that amorphous silicon solar cells emit 44 g CO_2/kWh of electricity generated compared to 75 g for multicrystalline cells. Another LCA published in the same year found that the installation of 2.5kW PV on the ground yields 141 g CO_2/kWh electricity generated, which is an

SOURCE	ENERGY PAYBACK RATIO	g CO_2/kWh
Renewable		
Hydroelectric		
With reservoir	48-260	4-18
Run of river	30-267	9-18
Photovoltaic	6-9	44-217
Wind		
Onshore	9.7	34
Offshore	16.5	18
Biomass		
Direct wood fire	27	400
Integrated biomass gasification Combined cycle	15	50
Nonrenewable		
Oil-fired plants	0.7-2.9	937
Coal-fired plants	2.5-5.1	1 000-1 154
'Clean' non-renewable		
Coal gasification combined cycle	3.5-7.0	—
Conventional boiler with CCS	1.6-3.3	340
Natural gas fire combined cycle	2.5	440

Table 12.1 EPR and CO_2 emissions of renewable and non-renewable energy sources

order of magnitude higher than hydro and wind, but an order of magnitude lower than coal.

For comparison, a summary of the EPR and CO_2 emissions of different renewable and non-renewable energy power plants are listed in Table 12.1 [3].

Conventional coal power plants have the highest emissions followed by oil, natural gas, biomass. Hydro and wind have the lowest emissions

As can be seen, conventional coal power plants have the highest emissions followed by oil, natural gas, biomass. Hydro and wind have the lowest emissions. Hydro and wind also have very favourable *EPR*. CCS (carbon capture and storage) reduces CO_2 emission of coal-fired plants by up to 70 percent but that is offset by a 60 percent reduction in *EPR*.

As can be seen, conventional coal power plants have the highest emissions followed by oil, natural gas, biomass. Hydro and wind have the lowest emissions. Hydro and wind also have very favourable *EPR*. CCS (carbon capture and storage) reduces CO_2 emission of coal-fired plants by up to 70 percent but that is offset by a 60 percent reduction in *EPR*.

The integrated biomass gasification combined cycle plant generates electricity with a gas turbine (from gasifying biomass) and the waste heat is used to make steam to generate additional electricity with a steam turbine. This enhances the efficiency of electricity generation, and most new gas power plants in North America and Europe are of this type. The energy ratio and CO_2 emissions look quite favourable.

Notably, modern combined cycle fossil fuel plants already perform as well or better than a conventional boiler plant fitted with carbon capture and storage.

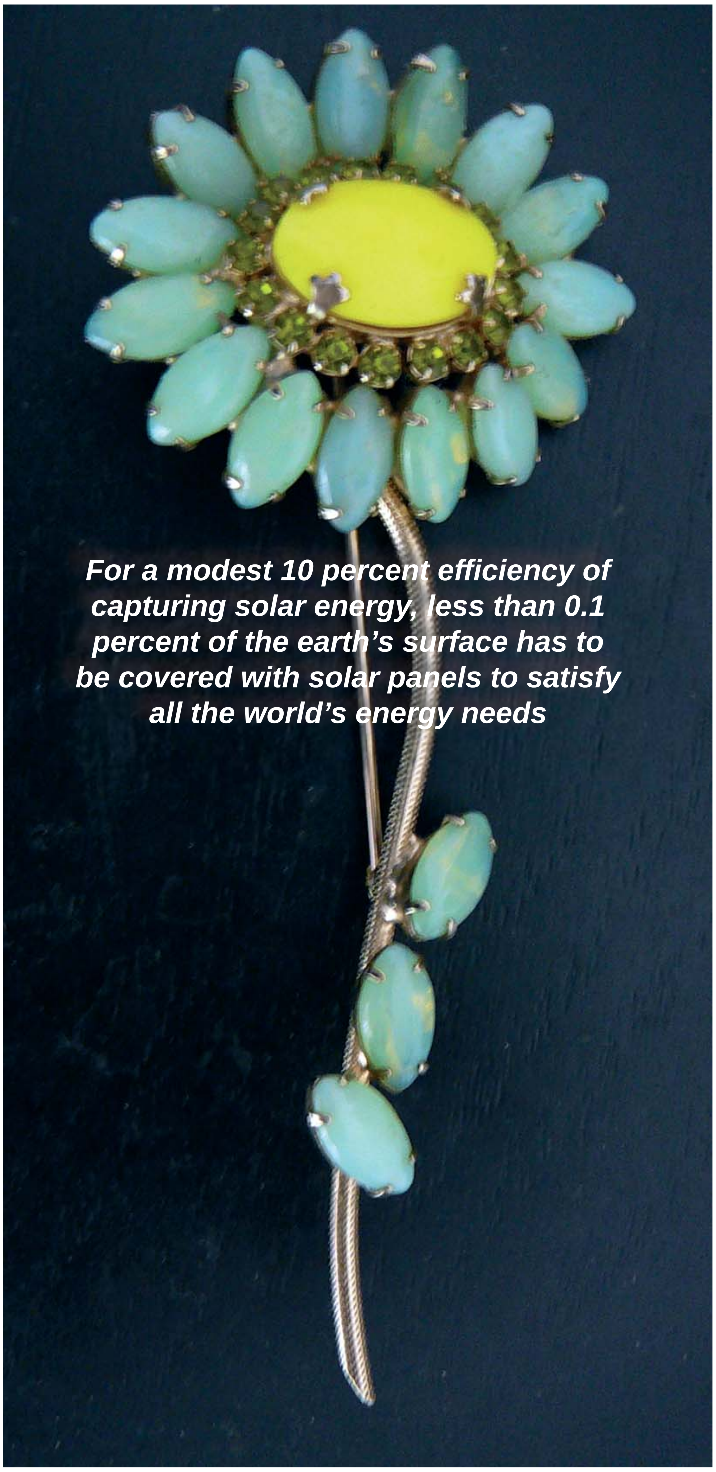
This LCA does not include environmental impacts, which are substantial especially for coal-fired plants and big hydroelectric dams.

Photovoltaic technologies are advancing rapidly; and the environmental indicators improve year by year [4] (see Chapter 14) and approaching those for wind

13

SOLAR POWER *TO* THE PEOPLE

Solar power on your own roof already as cheap as electricity from the grid



Sunflower brooch

GLOBAL POTENTIAL FOR SOLAR POWER

The world consumed 473 EJ (ExaJoule, 10^{18} J) of primary energy in 2008 [1]. This is equivalent to a power supply of 15 TW (TerraWatt, 10^{12} W). The total solar energy flux entering the earth's atmosphere is estimated at 174 PW (10^{15} W) [2]. Consequently, for a modest 10 percent efficiency of capturing solar energy, less than 0.1 percent of the earth's surface will satisfy all the world's energy needs.

Rapid technological improvements (see later) and savings from distributed local small scale and microgeneration could easily reduce the surface area required by an order of magnitude. Ease of manufacture and installation, modular design that could make use of any exposed surface such as roofs and walls, maximum flexibility, and minimum intrusion and maintenance, all contribute to the success of solar power. Solar power has topped the world's renewable energies capacity at least two years running [3] (see Chapter 11) and is set to grow further.

By far the greater capacity of solar power is in solar thermal, simply harnessing solar energy for heating or cooling, or producing electricity [4] (see Box 13.1). However, solar photovoltaic (PV), capturing sunlight to generate electricity (see Box 13.2), has undergone exponential growth since 2002, and is now the faster growing solar sector. Both solar thermal and PV are benefiting from concentrating solar power technologies

SOLAR THERMAL DOMINATES WORLD CAPACITY

Solar thermal (Box 13.1) is the more mature solar technology, and it experienced a record growth in 2007, driven by China [8], according to an EU report. It increased by 19 GW to reach 147 GW, the highest growth rate in a decade, and a similar expansion seems likely for 2008. China now has two-thirds of the global solar thermal capacity. The Chinese dominance is due to a lack of access to natural gas in many homes and affordable prices, coupled with a boost in government support for research and development. In the city of Rizhao, 99 percent of households use solar water heaters and benefit from savings in their energy bills Europe on the other hand experienced the first slowdown in the market in 2007, but preliminary

Box 13.1
SOLAR THERMAL

Solar thermal harnesses solar energy for heating, cooling, ventilation or producing electricity. Many different designs are possible from passive heat preservation, evaporation and convection, to active refrigeration using heat exchangers [4]. The US Energy Information Administration defines low-, medium- or high- temperature collectors. Low-temperature collectors are flat plates generally for heat swimming pools; medium-temperature collectors are usually flat plates for creating hot water in homes or commercial buildings. Both are widely installed for local distributed use.

High-temperature collectors, concentrating solar power (CSP) concentrate sunlight with sun-tracking mirrors or lenses to temperatures in excess of 600˚C, and are used for generating electric power with steam or gas turbines in solar power plants. The efficiency of heat engines increases with the temperature of the heat source. CSP effectively reduces the size of the collector and total surface area per unit power generated. But they are also more costly, and involve large capital investments. For example, parabolic trough power plants use a curved trough that reflects the direct solar radiation onto a pipe, the receiver, containing a heat transfer fluid – synthetic oil, molten salt or pressurized steam - running the length of the trough above the reflectors. The heated fluid transports heat to a heat engine that converts approximately one-third of the heat energy into electricity.

Other concentrating technologies [5] include: Dish Stirling, a stand-alone parabolic reflector that concentrates light onto a receiver positioned at the reflector's focal point; Concentrating Linear Fresnel Reflectors consisting of many thin flat mirror strips instead of parabolic mirrors, and are much cheaper to produce; Solar Chimney, a transparent large greenhouse sloped gently up to a central hollow tower or chimney, where the heated air rising up the chimney drives an air turbine to create electricity; and Solar Power Tower, in which an array of dual-axis tracking reflectors concentrate light onto a central receiver atop a tower, where a fluid, such as sea water, is heated to 500 – 1 000˚C and used as heat source for power generation or as energy storage system.

Concentrating solar technologies have also been applied to photovoltaics (concentrating photovoltaics (CPV, see Chapter 16), and a hybrid, concentrating photovoltaics and thermal (CPT). In May 2008, IBM demonstrated a prototype CPV using computer chip cooling techniques to achieve an energy density of 2 300 suns [6]. CPT can be used in private homes and increase total energy output to 40 to 50 percent as compared with normal PV panels with 10 to 20 percent efficiency, and they produce more heat in wintertime compared with normal thermal collectors [5].

Australia, US and Chinese researchers are exploring the potential for combined heat and power solar (CHAPS), while Europeans are now producing CHAPS.

figures for 2008 show a recovery with a strong rebound in the largest market of Germany and growing demand in the Mediterranean region.

CONCENTRATING SOLAR POWER TOO BIG

The SEGS (Solar Energy Generating System) in California, USA, using the parabolic trough design [4], is a collection of nine plants with a total capacity of 350 MW. It is currently the largest operating solar system. Nevada Solar One on the southeast fringes of Boulder City, with a capacity of 64 MW has been operating since June 2007 [9]. Two new CSP plants came on line in 2008, the 50 MW Andasol 1 in Spain and a 5 MW plant in California [10]. Andasol 2 in Spain, also with 50 MW capacity is under construction. The Andasol plants have heat storage which requires a smaller and better utilized generator. With day and night operation, Andasol 1 produces more energy than Nevada Solar one. CSP projects totalling more than 6 GW capacity are in the pipeline in the US, mostly planned for California, Arizona, and Florida. A further 3 GW projects have been announced in Europe, North Africa, and the Middle East; out of these, 2.5 GW are to be built in Spain. Israel and the United Arab Emirates opened tenders for projects totally 350 MW in the Middle East during 2008, and more are planned for Algeria, Morocco, and Egypt.

A study done jointly by Greenpeace International, the European Solar Thermal Electricity Association and the International Energy Agency's SolarPACES group found that CSP, under the most optimistic scenario, could account for up to 25 percent of world's energy needs by 2050 [11, 12]. Investment in CSP will reach €2 bn in 2009. Spain is leading the field with more than 50 projects approved and by 2015 will generate more than 2 GW power from CSP. Under the most optimistic scenario, the cost per kW would be €3 060 by 2015. The Greenpeace study is clearly in favour of big CSP plants.

The EU has begun to look into developing an

Rooftop solar installations

Box 13.2
SOLAR PHOTOVOLTAIC
Solar photovoltaic harvests energy from sunlight to generate electricity directly in a solar cell. The conventional solar cell (see Fig. 1) [7] is made from inorganic crystalline semi-conducting material such as silicon, which is 'doped' (slightly contaminated with appropriate elements) to form a p-n junction. The p side of the junction contains an excess of positive charges (holes), the n side, an excess of negative charges (electrons). This creates an electric field across the junction.

When sunlight is absorbed in the bulk of the silicon, free electrons and holes are created; these are accelerated by the electric field to go to the appropriate electrodes on the top and bottom of the cell (see Fig. 13.1). On reaching the electrode, the electrons leave the device to drive the external electric load, returning to recombine with the holes at the other, counter electrode.

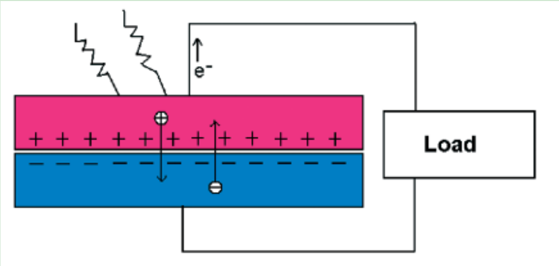


Figure 13.1 Diagram of a conventional solar cell

The conversion efficiency of the solar cell is defined as the ratio of the electric power provided to the external circuit to the solar power incident on the active area of the cell. It is typically measured under standard simulated conditions.

Susan Rigali's solar kitchen in Los Angeles, USA

ambitious €400 bn CSP plant in the Sahara known as Desertec, as part of a wider plan of "a new carbon-free network linking Europe, the Middle East and North Africa" [13]. The plan is backed mainly by German industrialists and predicts production of 15 percent of Europe's power by 2050. Critics warn of numerous pitfalls, including Sahara sandstorms and the risk, not only to Europe from having to import energy from Africa, but also to desert populations if their water is diverted to clean dust off solar mirrors. They point out rightly, that the CSP project involves much greater risks and costs due to heavy infrastructure than the fast-growing patchwork of smaller scale solar thermal and PV installations that generate most of Europe's solar energy today [14].

But, reinsurer Munich Re hosted the launch of Desertec in July 2009 at its headquarter in the Bavarian capital. They have yet to draw up a business plan or specify how it would be funded [13]

"Sahara power for northern Europe is a mirage," said Hermann Scheer, a member of Germany's parliament and head of the European Association for Renewable Energy. "Those behind the project know themselves that nothing will ever come out of this. He said that the costs of Desertec were being downplayed and the technical capabilities over-estimated.

For one thing it would need 20 or more efficient, direct-current cables costing up to $1 billion each to transmit electricity north beneath the Mediterranean.

Among the hazards of the scheme is that it requires tight coordination between governments to succeed, yet Maghreb (union of N. Africa) states have tried and failed for two decades to integrate their economies and deepen their political ties. The border between Morocco and Algeria remains shut and relations are poisoned by a disagreement over the Western Sahara.

Another risk of big solar installations is that like other big centralized power plants such as nuclear and 'clean coal' with carbon capture and storage, they would be obvious targets of malevolent attacks.

PV FORGING AHEAD

The year 2008 saw the most dramatic growth in PV [10]. Newly added PV power installations amounted to 5.6 GW, more than double the 2.4 GW installed in 2007. Cumulative PV power installed worldwide jumped from 9 GW in 2007 to nearly 14.5 GW in 2008. Europe remains the leading market for PV, accounting for more than 80 percent; and Spain overtook Germany to become number one in solar PV market worldwide, its capacity increasing from 0.56 GW to 2.6 GW from 2007 to 2008. Germany came second with 1.5 GW installations. The US came a distant third with 0.348 GW, followed by Italy, South Korea and Japan. At the end of 2008, Europe leads with more than 9 GW PV installed, or 65 percent of world PV capacity; leaving Japan and the US far behind with 15 and 8 percent respectively.

The phenomenal growth in the top two PV nations, Spain and Germany are due to government support programmes. A feed-in tariff policy in Spain requires utilities to buy electricity generated from solar power projects at premium guaranteed long-term prices set by the government. This resulted in unexpected enthusiasm from the industry. In September 2008 the government greatly reduced the payments under the feed-in tariff and put a cap on annual PV installation from 2009 through 2010 aiming at a target of 3 GW by the end of 2010. This is expected to slow the Spanish market in the coming years.

Germany also has a feed-in tariff programme for renewable energy; and it aims to reduce the premium solar electricity rates gradually until solar energy achieves price parity with conventional power. Payments for PVs declined considerably starting in January 2009, in line with a reduction in installation cost. The stability and consistency of Germany's feed-in tariff proved beneficial for continuous market development, and the country is expected to regain the lead in PV market in 2009.

Both crystalline silicon-based and thin-film polysilicon PVs saw dramatic growth in 2008, reaching 6.94 GW compared with 3.715 GW in 2007, an increase of 87 percent. The Chinese PV industry is leading in silicon-based cells, primarily to meet soaring demand from Spain and Germany. Japanese PV producers, once the world's leader, fell from their 2001 peak of 46 percent of world market to only 18 percent. The German company Q-Cells was top producer of solar cells in 2008; First Solar of USA ranked second, and Suntech of China came third.

Production of thin film polysilicon solar cells, cheaper though less efficient, grew 121 percent in one year, from 0.432 GW in 2007 to 0.954 GW in 2008; its global share rising from 7 percent in 2007 to 13.7 percent in 2008. The US leads in thin films production. Industry leaders include First Solar, which has manufacturing plants in the United States, Germany, and Malaysia, and United Solar. First Solar recently completed the largest thin-film solar power plant to date in North America, a 10-MW facility in Nevada. In 2008, developers in Germany commissioned three new large-scale thin-film PV installations with a combined capacity of some 50 MW. Also in 2008, Masdar PV announced a multibillion-dollar investment in thin-film PV facilities in Germany and Abu Dhabi-one of the largest investments ever made in solar power.

Cumulative PV power installed worldwide jumped from 9 GW in 2007 to nearly 14.5 GW in 2008

GRID PARITY HERE

Costs of solar and other energies are usually quoted per kW or per kWh. The former is an installation cost of the rated power, and does not take into account the amount of sunlight received at the location, the performance or life time of the installation. The latter is the actual cost per unit of energy delivered, taking into account the local insolation, the performance and life time of the installation.

Some reports are claiming that the true cost of solar power is now less than $0.25 per kWh in most locations, and likely to reach $0.1 per kWh by 2010 [15]. Already solar is at a cost that makes it competitive with the grid in OECD's highest-priced markets. An estimated 5 to 10 percent of OECD residential grid electricity of 200 to 400 TWh is above the cost of solar power.

PV technologies have been improving by leaps and bounds while manufacturing costs are still dropping. If grid parity is not quite here for all electricity supply, it will surpass it in the next few years. One technology to watch is new thin-film PVs.

NEW THIN FILM TECHNOLOGIES

New thin film PVs are less efficient but more than make up for that in being much cheaper and easier to manufacture. 'Second generation' thin film PVs include cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) applied in a thin film to a supporting substrate such as glass, flexible metallic foils, high-temperature polymers or stainless steel sheets [14]. In 2007, the US-based company First Solar produced 200 MW of CdTe solar cells making it the fifth largest producer of solar cells in 2007, and first ever within the top 10 producing only second generation PV. Nanosolar commercialised its CIGS technology in 2007 with a production capacity of 430 MW for 2008 in US and Germany. In 2007, CdTe production represented 4.7 percent of total market share, thin film silicon 5.2 percent and CIGS 0.5 percent.

The first company to manufacture thin-film PV, Unisolar, located in the US and Europe, currently makes thin film solar cells at under $1 per watt [16].

CIGS thin film PVs reached a lab efficiency of

Box 13.3
QUANTUM DOT POSSIBILITIES [22]

Quantum dots or nanoparticles are semi-conducting crystals of nanometre (a billionth of a metre) dimensions. They have quantum optical properties that are absent in the bulk material due to the confinement of electron-hole pairs (called excitons) on the particle, in a region of a few nanometres.

The first advantage of quantum dots is their tunable band gap. It means that the wavelength at which they will absorb or emit radiation can be adjusted at will: the larger the size, the longer the wavelength of light absorbed and emitted. The greater the band gap of a solar cell semiconductor, the more energetic the photons absorbed, and the greater the output voltage. On the other hand, a lower band gap allows the capture of more photons including those in the red end of the solar spectrum, resulting in a higher output current but at a lower output voltage. Thus, there is an optimum band gap that corresponds to the highest possible solar-electric energy conversion, and this can also be achieved by using a mixture of quantum dots of different sizes for harvesting the maximum proportion of the incident light effectively.

Another advantage of quantum dots is that in contrast to traditional semiconductor materials that are crystalline or rigid, quantum dots can be molded into a variety of different form, in sheets or three-dimensional arrays. They can easily be combined with organic polymers, dyes, or made into porous films [21]. In the colloidal form suspended in solution, they can be processed to create junctions on inexpensive substrates such as plastics, glass or metal sheets.

When quantum dots are formed into an ordered three-dimensional array, there will be strong electronic coupling between them so that excitons will have a longer life, facilitating the collection and transport of 'hot carriers' to generate electricity at high voltage. In addition, such an array makes it possible to generate multiple excitons from the absorption of a single photon [22]

Quantum dots are offering the possibility of improving the efficiency of solar cells in at least two respects, by extending the band gap of solar cells for harvesting more of the light in the solar spectrum, and by generating more charges from a single photon.

19.9 percent, and achieved an efficiency of 13 percent in mass production recently [17]. CdTe flexible thin-film cells have reached an efficiency of 12.4 percent [18]. These cells are printed on a lightweight polymer film using a low temperature (< 450 ˚C) vacuum deposition to grow CdS/CdTe layers and a subsequent annealing step in air. This 12.4 percent uses ZnO:Al as a transparent electrical contact instead of the expensive ITO (indium tin oxide) layer used earlier in an 11.4 percent efficiency solar cell.

Thin film solar cells are flexible and can be fitted onto any available surfaces of buildings such as walls as well as roofs, or even windows as some of them are transparent.

Nanosolar panels

Nanosolar has produced the cheapest solar cells on the market at 12 percent module efficiency, which will sell for $1/Watt

BRIGHTER & CHEAPER YET

Third generation technologies aim to improve the efficiency of second generation thin film technologies to 30-60 percent while maintaining very low production costs. Thin-film solar cells use less than 1 percent of the raw material compared to wafer based solar cells, leading to a significant drop in price per W [19]. (The current US target is US$1/W generating power.) One of R& D Magazine's prestigious R&D 100 Awards - also called the "Oscars of Invention" - for 2008 has gone to the US National Renewable Energy Laboratory hybrid CGIS cells manufactured by using ink-jet and ultrasonic technologies to precisely apply metal-organic inks in separate layers directly onto a common substrate.

Many developments are underway to increase efficiency and cut costs [20].

We have shown earlier in our 2006 report [21, 22] that quantum dots are offering the possibilities for improving the efficiency of solar cells in at least two respects, by extending the band gap of solar cells for harvesting more of the light in the solar spectrum, and by generating more charges from a single photon (see Box 13.3). Solar cells based on quantum dots could theoretically convert more than 65 percent of the sun's energy into electricity, approximately doubling the efficiency of solar cells.

Another current strategy to increase efficiency is to target solar concentrators, devices for increasing solar intensity. Current PV concentrators track the sun to generate high optical intensity, often by using large mobile mirrors that are expensive to make, install and maintain (see earler).

Researchers at the Massachusetts Institute of Technology (MIT) in the US have created a new solar concentrator based on light absorbing organic dyes. In their invention, sunlight falls on the first organic solar collector (OSC) with a dye absorbing at low wavelengths but transmits the rest to a second OSC underneath with a dye absorbing at longer wavelengths. Alternatively, solar radiation transmitted through the top OSC can be gathered by a bottom PV cell or used to heat water in a hybrid PV thermal system. The first dye re-emits light at a longer wavelength which is largely trapped inside the glass, and can be used by PV cells stuck to the sides to generate electricity. Similarly, the dye in the second OSC, on absorbing light at long wavelengths, re-emits at a still longer wavelength that ix also largely trapped within the layer so the PV cells stuck to its sides are able to generate electricity [23, 24]. This array of OSCs overlying ordinary solar cells can boost the overall efficiency by 20 to 30 percent, and bring down the cost of PV electricity substantially, perhaps by 10 fold. The MIT researchers used DCJTB (4-(dicyanomethylene)-2-t-butyl-6-(1,1,7,7-tetramethyljulolidyl-9-enyl)-4H-pyran) and Pt(TPBP) (platinum tetraphenyltetrabenzoporphyrin) together with various host materials.

A third strategy is to use transparent thin films that are also conductors of electrical charge [18]. It allows light to pass through to the light absorbing material beneath, and also serves as an electrical contact to transport charge carriers away from the light absorbing material, thereby increasing the efficiency. These include various transparent conductive metal oxides. Physicist Bram Hoex and colleagues at Eindhoven University of Technology, together with the Fraunhofer Institute in Germany succeeded in boosting the efficiency of a crystalline silicon solar cell by 6 percent, from 21.9 to 23.3 percent. This is achieved by depositing an ultra-thin (30nm) layer of aluminium oxide at the front of the cell [25]. The layer has a high concentration of negative charges, almost entirely eliminating tenergy loss through the surface of the cell.

One third generation solar company that appears ahead of its competitors is Nanosolar. Nanosolar has developed the world's largest solar cell factory in California, USA, and the largest solar panel-assembly plant in Germany. Its solar cells are essentially copper indium gallium diselinide (CIGS) thin-film, but with important differences that give them a place among third generation solar cells as they are made from a quantum dot [22] coating that is printed onto a highly conductive metal foil substrate using roll to roll printing facilities.

Nanosolar, based in San Jose, California in the US, recently revealed the efficiency of its solar cells at 16.4 percent, reaching a module efficiency of about 12 percent [26]. These solar cells have been rumoured to cost $0.30/Watt [27] and Nanosolar plans to sell its solar PV modules at $1/Watt [28]. If Nanosolar's solar cells do cost $.30/Watt or even $.50/watt to manufacture, they would be the cheapest solar cells on the market as the current record for thin-film solar cells is just under $1/Watt manufactured by Unisolar and First Solar.

Nanosolar's high cell and module efficiency also puts their solar cells in the same league as silicon solar cells. Nanosolar also claims their solar cells will withstand extreme heat and cold and come with a 25 year warranty, also matching crystalline silicon PV.

Some examples of third generation PV cells will be described in more detail in Chapters 15 – 17.

14

SOLAR POWER GETTING CLEANER *FAST*

New thin-film solar panels cheapest and cleanest and getting better yet

As photovoltaic (PV) technologies are progressing rapidly in boosting efficiency and bringing manufacturing costs down, their environmental indicators are also improving.

A lifecycle assessment (LCA) of PV technologies based on data of rooftop installations under Southern European insolation (incident solar radiation) of 1 700 kWh/m2/y found an energy payback time (*EPBT*) of 1.7, 2.2, 2.7 and 1.1 years respectively for ribbon-silicon, multicrystalline silicon. monocrystalline silicon, and thin-film CdTe (cadium tellurium) systems [1]. *EPBT* is the time it takes for the device to generate as much energy as had gone into producing it [2] (see Chapter 11). The *EPBT* of the CdTe PV was much smaller than the other systems although its electrical-conversion efficiency was the lowest at 9 percent, compared with 11.5 percent for ribbon, 13.2 percent for multicrystalline, and 14 percent for monocrystalline silicon.

A follow-up study updated the LCA and presented the 'cradle-to-gate' emissions of GHG and heavy metals of the same four commercial PV systems based on the most recent data (2004-2006) [3]. These are largely indirect emissions associated with the use of fossil fuels in the lifecycle of the PVs. Direct emissions of heavy metals from mining and smelting are also included, whereas liquid and solid wastes are for the most part being recycled, and so were not considered in the study. The choice of electricity and fuel sources is important in determining the total emissions.

For silicon PV, the data from 11 commercial European and US PV module manufacturing companies were supplemented by numbers from the literature. Each module assembly typically consists of 72 (0.125 m x 0.125m) solar cells with silver contacts at front and back sides. Ethylene-vinyl acetate and glass sheets encapsulate the PV module to protect it from the elements during operation. Crystalline silicon modules typically have aluminium frames for additional strength and easy mounting.

The CdTe PV module gives the lowest GHG emissions at just over 20 g CO_2 equivalent per kWh. It also gives the lowest emissions of nitrogen oxides and sulphur oxides

The lifecycle of silicon PV modules starts with the mining of quartz sand. The silica in the sand is reduced in an arc furnace to obtain metallurgical grade silicon, which is then purified further into electronic grade or solar grade silicon. This is done either by the Siemens process in which silane and hydrogen gases are heated to 1 100-1 200˚C for growing silicon rods, or the modified Siemens process in which they are heated to ~800˚C.

Data from CdTe PV modules in commercial production were from a manufacturing plant in Perrysburg Ohio in the United States. The typical frameless CdTe modules are 1.2 m x 0.5 m with electricity conversion efficiency of 9 percent (though this had increased to 12.4 percent by August 2009).

Cd is obtained from a waste stream of Zn smelting. Te is recovered from the slimes produced during electrolytic copper refining. Cd is further purified either through leaching and vacuum distillation, or through electrolytic purification followed by melting and atomization or vacuum distillation. Te is also further purified by the same methods. CdTe is produced finally via proprietary processes.

The CdTe absorber layer and cadmium sulphide (CdS) window layer are laid down by vapour transport deposition based on subliming the powders and condensing the vapours onto glass substrates. A stream of inert carrier gas guides the sublimed dense vapour cloud to deposit the films at 500-600˚C with a growth rate of 1 micrometre per second. The interconnections and back contacts are formed by depositing a layer of common metals followed by series of scribing and heat treatment

GREENHOUSE GASES & OTHER EMISSIONS

The results of the lifecycle emissions using different databases are presented in Figure 14.1. Case 1 is the current electricity mixture in Si production, CrystalClear project and Ecoinvent database. Case 2 is the Union of the Co-ordination of Transmission of Electricity (UCTE) grid mixture and Ecoinvent database. Case 3 is the US grid mixture and Franklin database. The conditions used are the Southern European average insolation of 1 700 kWh/m²/y, a performance ratio of 0.8 and a lifetime of 30 years. The performance ratio is the real output of energy compared with the theoretical maximum output.

As can be seen, the CdTe PV module gives the lowest GHG emissions at just over 20 g CO_2 equivalent per kWh. It also gives the lowest emissions of nitrogen oxides and sulphur oxides.

HEAVY METAL EMISSIONS

The CdTe PV can emit Cd both directly and indirectly, whereas the crystalline Si PV would emit it only indirectly. The total direct Cd emissions from the lifecycle of CdTe PV modules coming from mining, smelting, purification of the element and the synthesis of CdTe are 0.015 g/GWh. The total direct emissions of Cd during module manufacture are 0.004 g/GWh. Emissions during accidental releases such as fires are extremely small, if any. The total direct emissions of Cd make up 0.02 g/GWh.

Indirect Cd emissions come from the generation of electricity used in producing all parts of the PV module, for providing heat and mechanical energy during materials processing, for climate control of the manufacturing plant, and for transport of materials and products. The Cd is contained in fossil fuels burnt, a fraction of which is released into the atmosphere during combustion. The dominant sources of such indirect Cd emissions are from coal burnt during steel-making processes and during glass-making from the boiler materials and from the electricity supply needed in the boiler.

The results show that CdTe PV actually prevents a significant amount of Cd from being released to the atmosphere. Every GWh electricity generated by CdTe PV module can prevent about 4 g of Cd emissions. The direct emissions of Cd during the lifecycle of CdTe PV are 10 times lower than the indirect emissions, and about 30 times lower than those indirect emissions in the lifecycle of crystalline PVs.

However, Cd is extremely toxic, even at very low concentrations [4]. Anco Blazer, a thin film specialist who has worked with CdTe PV modules, points out that there is a substantial risk of mass release of Cd into the environment in the event of an earthquake, should large numbers of such panels be fitted in earthquake zones of California, for example. Efforts should be made to substitute safer alternatives in the fabrication of PVs as these are becoming common household fixtures.

There is major scope for improving the environmental indicators while simplifying the manufacturing processes and reducing costs. For example, thin-film modules can be manufactured by ink-jet printing techniques and flexible metal sheets used as substrate [2].

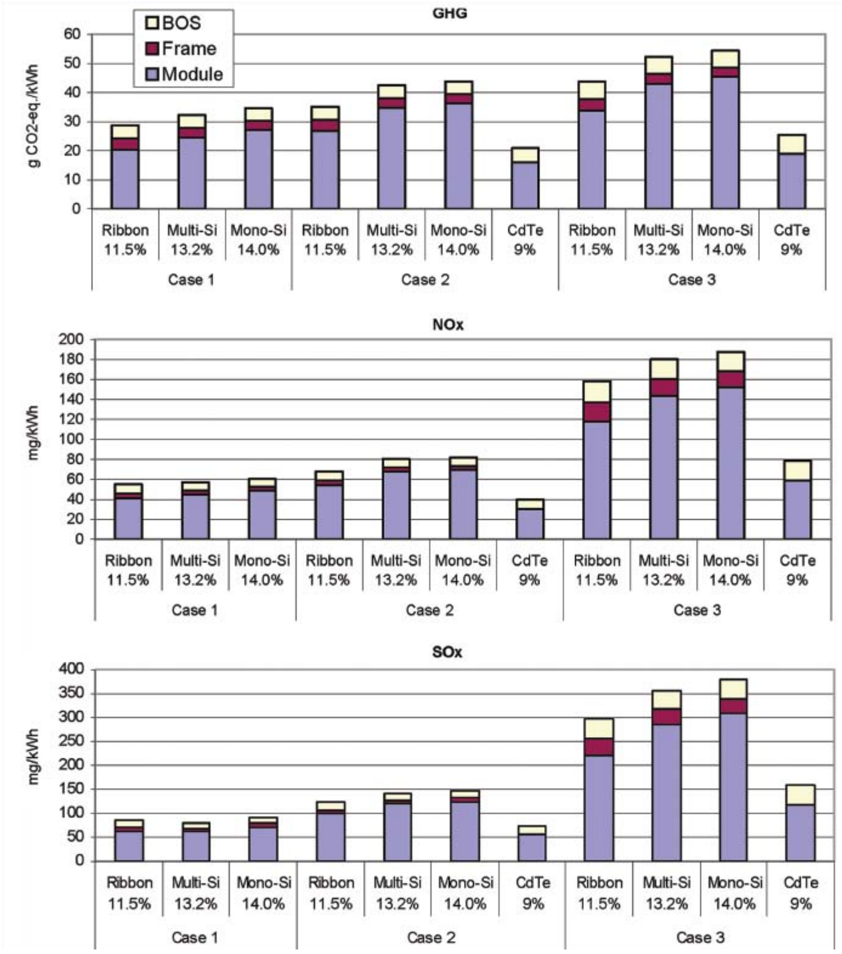


Figure 14.1 Lifecycle emissions from silicon and CdTe PV modules BOS is the Balance of System (module supports, cabling and power conditioning).

Cd is extremely toxic, even at very low concentrations there is a substantial risk of mass release of Cd into the environment in the event of an earthquake, should large numbers of such panels be fitted in earthquake zones of California

15

QUANTUM WELL SOLAR CELLS

Trapping solar energy in quantum wells increases gain and efficiency

A ‘quantum well’ is a potential well that confines to two dimensions particles that are otherwise free to move in three dimensions. The effect is to increase the gain and efficiency of the solid state devices such as lasers in CD or DVD players, infrared imaging, and more recently, solar cells.

HOW QUANTUM WELLS TRAP SOLAR ENERGY

A quantum well is basically a semiconductor with a small energy gap (or band gap) sandwiched between two thicker layers of semiconductor(s) with a large energy gap, such as gallium arsenide (GaAs) (see Chapter 12 for a description of a solar cell [1]). Quantum wells in solar cells confine electrons and holes to two dimensions. The number of electrons and holes confined is determined by the thickness of the semiconductor used, usually ranging from 1-10 nanometres. Confining electrons within quantum wells allows them to be easily converted to useful forms of energy, and it is the thinness of the semiconductor material that allows this to happen.

Quantum well solar cells are built with multiple nanoscale semiconductors layered on top of one another with a lateral conduction layer between

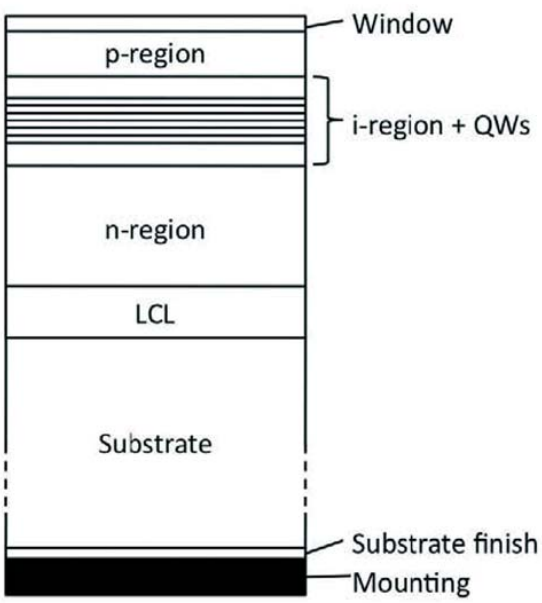


Figure 15.1 Quantum well solar cell. QW – Quantum Well. LCL – lateral conduction layer [2]

the substrate and the n region to allow contact between each device (Fig. 15.1). The quantum wells are in the thin i layer in a p-i-n junction. Within the i layer, the potential energy of an electron is less than the outside layer so the flow of charge is confined to certain well-defined regions and can be exploited in solar photovoltaics. Quantum wells are grown by molecular beam epitaxy, where atoms of the materials are delivered to crystals using a molecular beam, or through chemical vapour deposition, using a flow of gas.

A QUANTUM SOLAR JOURNEY

Professor Keith Barnham of Imperial College London, who invented the quantum well solar cell in 1989, was originally funded by Greenpeace Environmental Trust. Barnham is now Chief Scientific Officer and Director of QuantaSol, a UK-based solar PV company that will bring quantum well solar cells to the solar industry. These solar cells operate at high current. The i region consists of alternating layers of indium gallium arsenide (InGaAs) and gallium arsenide phosphide (GaAsp), while the p and n layers of the solar cell are made from gallium arsenide GaAs. A “strain balance” technique used to grow the different layers, matches the lattice structures of the different semiconducter materials, preventing defects [3]. This method allows more than 65 wells to be grown on top of one another without dislocation [2].

The band gap of Barnham’s single junction quantum well solar cell is also better matched to the solar spectrum at 1.33 eV than a 1.42 eV gallium arsenide (GaAs) solar cell [4] (see [5] Chapter 16). Quantum well solar cells avoid efficiency losses that plague most solar cells because the quantum wells have a lower band gap than the rest of the cell as illustrated in Fig. 15.2. The band gap (V) is higher than the absorption threshold (Ea) of the quantum wells; this allows electrons to enter the wells after being hit by incoming lower-energy photons, contributing extra current [6]. It also reduces the dark current, which is generated from the potential difference between the terminals of the PV cell and flows in the opposite direction to the photocurrent, decreasing net efficiency. A 1 cm x 1 cm multi-junction quantum well solar cell can reach a high current of 7 Amps at 500x solar concentration [4].

Like conventional solar PV for micro-generation, the cost per kWh for industrial scale solar PV depends largely on environmental factors such as the amount of solar insolation (the solar power density incident on a surface of stated area and orientation, usually expressed as Watts per square metre) and solar cell efficiency. Assuming a full life cycle of 25 years for the concentrating photovoltaic (CPV) power plant, the best estimate today would be near US$0.20 per kWh. QuantaSol expects to be competitive with current CPV rates if not better. In comparison, current global average cost per kWh for a 2 kW residential system is US$0.37 in a "sunny climate" and US$0.81 US per kWh in a "cloudy climate" [7]. This does not include government rebates, such as feed-in tariffs in countries like Germany, so prices for individual countries will vary. Projected costs are expected to continue to drop in the future as manufacturing costs go down. China, for example, is planning to reduce the cost of generation to US$0.146 per kWh by 2012 [8]. Another obstacle to overcome in making solar electricity more affordable is storing solar energy [9] (see Chapter 26) for when it is not available at night. For solar electricity to be more sustainable and reliable, new storage technologies must be developed, especially in using solar light to break down water into hydrogen and oxygen in artificial photosynthesis [10] [11] (see Chapters 27 and 28).

PHOTON RECYCLING

As losses are due to charge recombination, quantum wells create a more efficient cell by allowing researchers to adjust the band gap to minimise recombination. "If you adjust the band gap you can adjust how much [energy] each cell produces," said Barnham.

Once recombination is controlled in order to get the most current possible, the next step is to find ways of recovering losses of light absorbed by the cells through photon recycling [3]. Photon recycling can prevent incoming high-energy photons from being wasted as heat.

To recycle photons, a reflector is used to reflect light back to the cell so it can be reabsorbed to increase the current. Reflectors used include the Distributed Bragg Reflector (DBR, also used in fibre optics) and the Luminescent Solar Concentrator (LSC) doped with quantum dots or nano-rods to increase light absorption.

Barnham and his team discovered that internal reflection within the cell is often the best form of photon recycling. In some cases an air gap is all that is needed [3]. Reflecting back photon losses onto the solar cell results in an increase of 1.5 percent efficiency for single junction solar cells and potentially more for multi-junction solar cells.

NEW SOLAR WORLD RECORD

Barnham and his team currently hold the record for the most efficient nano-structured solar cell at 30.6 percent, obtained from a tandem-junction quantum well solar cell at a concentration of 54 suns. One sun is about the amount of light that makes it to the Earth on a sunny day. Recently,

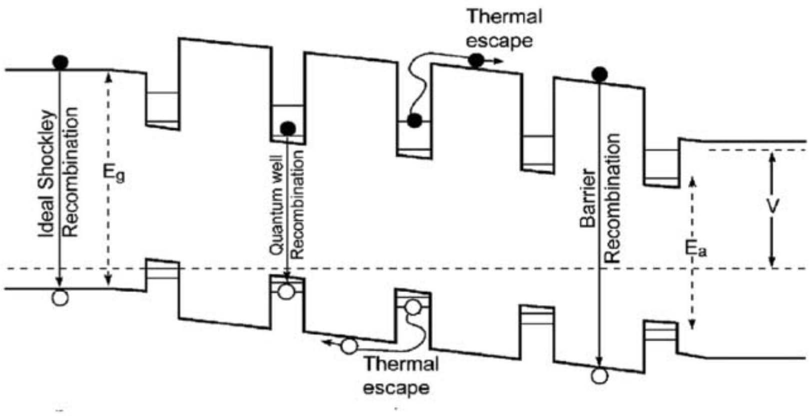


Figure 15.2 Strain-balanced quantum well solar cell [3]

their gallium arsenide phosphide and indium gallium arsenide (GaAsp/InGaAs) single junction solar cell has also broken the world record (28.2 percent) for single junction cells at 28.3 percent with a concentration of 500+ suns.

Barnham and his team currently hold the record for the most efficient nano-structured solar cell at 30.6 percent, obtained from a tandem-junction quantum well solar cell at a concentration of 54 suns

COST & LIFE CYCLE

The life-cycle assessment (LCA) [12] (see Chapter 12) of solar PV cells provides an indicator of how well solar cells perform in terms of energy payback and emissions of greenhouse gases from 'cradle to grave'. According to recent studies on concentrating solar PV life cycles, the energy payback time (EPBT) is currently 0.7-1.3 years for one concentrating system examined, SolFocus [13]. This is slightly better than rooftop silicon PV solar cells that have an EPBT of 1.1-2.7 years. Based on recent analyses, the amount of greenhouse gases emitted by concentrating solar PV is not yet known, but for silicon solar cells it is 30-55 g/kWh and CdTe (cadmium telluride thin film PV) is 21-25 g/kWh (see Chapter 14).

QuantaSol plans to make their quantum well solar cells commercially available to solar concentrator manufacturers early in 2010. Their goal is to develop quantum well solar cells specifically tailored to the spectral conditions in relation to the placement of concentrators and to optimise both for peak efficiency for utility-based solar PV. In time, as the costs come down, quantum well solar cells with concentrators could be used for micro-generation and other conventional solar PV applications. QuantaSol is currently researching how its quantum well solar cells will perform under different environmental conditions to get the best possible cost per kWh.

16

VERY HIGH EFFICIENCY SOLAR CELLS

Highest efficiency solar cells use innovations in optics to concentrate sunlight

CONCENTRATING SOLAR CELLS

Much progress has been made in utilising new materials to produce low efficiency, low cost solar cells, but currently the backbone of the global solar industry is still silicon. The same semiconductor material that built the physical infrastructure of the IT revolution also forms the basis of the solar energy revolution. Today, the largest demand for silicon comes from the solar industry, with Europe accounting for over 80 percent of global solar photovoltaic (PV) demand in 2008, followed by the US, South Korea and Japan [1]. Solar cells made from silicon and other PV materials have reached efficiencies over 40 percent. These high efficiencies are achieved by concentrating solar light onto devices with three or more solar cells. New pathways of research are also opening up to develop methods of storing solar energy through artificial photosynthesis [2] (see Chapter 27) that potentially could be used in tandem with solar technologies, such as very high efficiency solar cells..

High efficiency solar modules appear to be primarily for industrial application so far. But the goal of many PV researchers is to make these devices cheaper for micro-generation in the commercial markets. There are a number of strategies to accomplish this. One is to develop super efficient solar PV cells to produce a higher power output that compensates for the material costs. Another is to make relatively low efficiency solar cells with cheaper materials as in the case of organic, dye sensitised and amorphous silicon solar cells [3]. Using solar concentrators or reflectors in conjunction with highly efficient silicon solar cells has been the most popular method for solar researchers.

NEW WAYS TO CONCENTRATE SUNLIGHT

Professor Allen Barnett and a team of solar researchers at the University of Delaware along with more than 12 other organisations in the US have developed the highest efficiency solar PV device in the world so far. They plan to develop a solar cell module of 50 percent efficiency, a project funded by the Defense Advanced Research Projects Agency (DARPA) and managed by the chemical company Dupont. Once fully developed, it could be the highest efficiency solar PV device for commercial application.

The solar PV device being developed by Barnett, the principal investigator of the project, and the Very High Efficiency Solar Cell (VHESC) team uses a lateral optical concentrator that tracks the sun to focus sunlight onto different solar cells. Each solar cell in the device consists of multiple junctions such as gallium indium phosphide and gallium arsenide (GaInP/GaAs), gallium indium arsenide phosphide and gallium indium arsenide (GaInAsP/GaInAs) [4], and silicon filtered by GaAs at 20-50 suns. In order to test how this design works, researchers concentrated sunlight using a double-convex lens. This then guided it to a dichroic mirror where it is split into two bands of light for absorption by the sub-module made up of “low” and “mid-energy” tandem solar cells as shown in Fig. 16.1. The same design would be used for a device with more solar cells.

Dichroic mirrors are used in LCD projectors because they divert infrared light away from the light bulb to prevent over-heating. Dichroic materials are also used in jewellery and architecture because they reflect many bright and beautiful colours. In the application for solar cells, Barnett says they have high optical efficiency and virtually no losses due to absorption, and replace

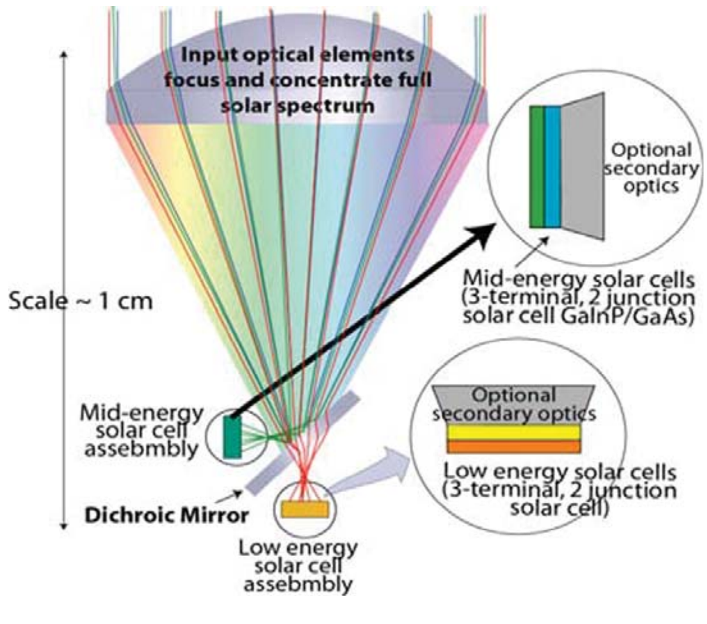


Figure 16.1 The dichroic mirror diverts two bands of light to be absorbed by two different tandem solar cells of the sub-module tested [5]

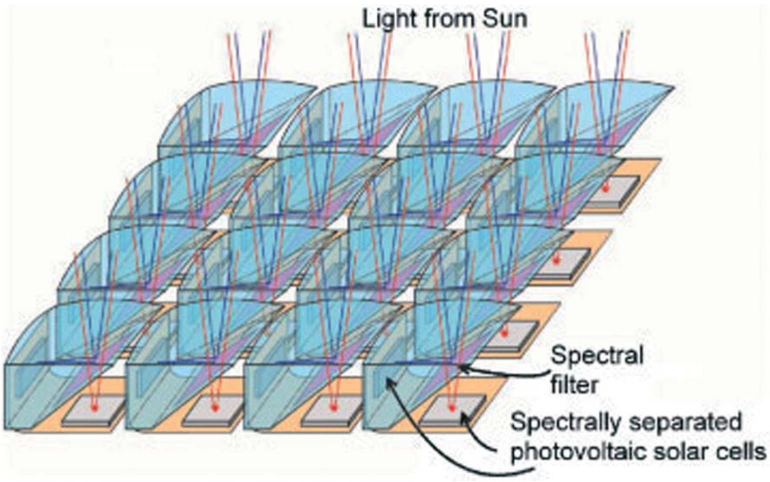


Figure 16.2 Tiled non-imaging concentrating system that concentrates sunlight onto solar cells arranged laterally to absorb different parts of the solar spectrum [5]

the prisms that have been used previously with multi-junction solar cells.

"The mirrored approach is one of the innovations of this work," said Barnett. Another important factor is that the solar cells do not need to be in electrical series to produce power. "We really opened the design space and having done that, there is a lot more we can do," he said. In other multi-junction solar modules, solar cells are stacked together in order to absorb different bands of light. In this design they are parallel which also allows each solar cell to be optimised for absorbing different parts of the solar spectrum. Each solar cell in the module has separate electrical contacts, eliminating the need for electrical series connections of the solar cells. As the solar cells are arranged laterally, this also reduces the need for them to be connected in optical series (see Fig. 16.2).

Non-imaging optical concentrators such as the one used by the VHESC team reach high optical efficiencies because the concentrator guides the photons to the receiving solar cells directly without creating an image

NON-IMAGING OPTICS

While the sum of the efficiencies of each solar cell used in the sub-module is high, recently measured at 44.3 percent [6], individual solar cell efficiency is only part of making a solar PV device that performs well. For multi-junction solar cells using concentrators, optics is crucial as the more sunlight concentrated onto the solar cells, the greater is the module's efficiency. This is where non-imaging optics comes into the VHESC team's design, allowing concentrators to achieve ultra high optical efficiencies.

Non-imaging optics was originally discovered by Dr. Roland Winston at University of California, Merced in the US in the 1970s. Winston has used non-imaging optical designs for solar thermal energy concentrators through the company SolarGenix Energy based in Chicago, Illinois [7]. The non-imaging optics concentrator designed by Winston is "essentially a funnel" where light enters from a large area and is reflected as it passes through a smaller area. "With non-imaging optics you don't need the image of the sun to hit your target, only the photons, so once you reduce the need for an image the opportunities for concentration increase significantly," said Barnett. The solar device designed by the VHESC team uses a tiled non-imaging concentrating system that concentrates incoming sunlight onto the solar cells (see Figure 15.2). Non-imaging optical concentrators such as the one used by the VHESC team reach high optical efficiencies because the concentrator guides the photons to the receiving solar cells directly without creating an image. For example, in order to concentrate light with a magnifying glass it requires an image to transfer light from one point to another, but is limiting in terms of optical efficiency. In order for a lens to create an image, light must be reflected in a particular way, but if an image is not needed then light can be transferred directly for the purpose of concentrating light onto solar cells. The tiled design of the non-imaging concentrating system allows sunlight to be focused onto each solar cell in this way. Although a sun tracker has been used with the sub-module, the non-imaging concentrator itself is static and does not need to track the sun in order to concentrate sunlight.

HIGH EFFICIENCY SOLAR CELLS TO MARKET SOON?

According to Barnett, in order to reach their current goal of 40 percent module efficiency, some of the solar cells need to be close to 43 percent. As the solar cells do not need to be connected in series, Barnett and his research team to "pick the best of the solar cells, not just the best of the ones that can be grown together." Barnett says different combinations of materials can be used including germanium, gallium, arsenide, indium and silicon, along with other materials to design a new high efficiency solar device with six junctions [6].

Once the VHESC team reaches 40 percent module efficiency, Barnett expects to see a commercial prototype in 2 years time. Recently, the team reached 39.5 percent sub-module efficiency at 30.48 x concentration [6]. Barnett says this project has attracted the attention of individuals and companies throughout the solar industry. "Utilities are very enthusiastic about the potential, the more higher efficiencies become available the more opportunities increase," he said. "I think the utilisation of solar power [electricity] is in its infancy."

17

THIRD GENERATION SOLAR CELLS

Advances in organic and hybrid solar cells helping to create a solar powered society

Research in organic and dye sensitised solar cells (DSSCs) continues to make breakthroughs thanks to innovative university scientists throughout the world and astute solar companies striving for third generation solar cells that are more affordable.

ORGANIC SOLAR CELLS ADVANCING

ISIS' 2006 energy report [1] mentioned the company Konarka Technologies in the US planning to increase the efficiency of their organic solar cells to 10 percent within 3-5 years.

Konarka's organic solar cell (see Fig. 17.1), invented by Professor Alan J. Heeger at University of California, USA, essentially consists of a polymer that releases electrons when exposed to sunlight, blended together with fullerenes (carbon nanostructures) (PL) that carry the electrons away from the polymer to form an electric circuit [2]. Organic solar cells use extremely thin materials as the excitons (electron-hole pairs) only spread out about 10 nanometres (10 billionths of a metre). The organic materials must be constructed on a nanoscale intimately blended with fullerenes in order to maximize the absorption of incoming light and for the fullerenes to guide electrons and holes away without recombining.

Organic solar cells are flexible, light weight and can be made transparent to be used in windows for urban buildings, for example. One of their main advantages over silicon solar cells is that their reflection coefficient is very small, so whether the sun is high or low in the sky they will reflect much less light back into the environment. The manufacturing cost of organic solar cells depends on the application, but they are aimed to be competitive with flexible thin-film solar cells at $3-5 per Watt. With a solar cell of 6.5 percent efficiency recently achieved by Konarka, that could lower prices further. "The efficiency and the cost are intimately coupled and that's going to be playing out over the next couple of years," said Heeger. The main problem is the short life time of the solar cell.

The organic solar cells originally produced by Konarka used a polythiophene polymer (Fig. 17.2) that doubles the power output of single cells by absorbing both infrared and ultraviolet light, including a top layer that absorbs blue and green light. However, Heeger and researchers at Konarka are working on second and third generation polymers with better properties, as the polymers used in the past have too large an energy gap. "Most of the energy we receive from solar radiation is in the infrared outside of the visible range, so we have to design and synthesise polymers which have a smaller energy gap, so we can efficiently harvest light," said Heeger.

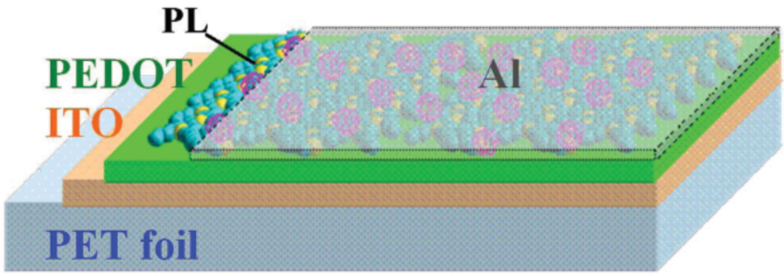


Figure 17.1 Organic solar cell. PET, Polyethylene terephthalate (substrate); ITO, Indium Tin Oxide (base electrode); PEDOT, Poly (3,4-ethylenedioxythiophene) poly(styrenesulfonate) (conductive polymer); PL, photoactive layer (polymer-fullerene blend); Al – Aluminium (top electrode).[Wikipedia Creative Commons]

Konarka's 10 percent efficiency goal has not yet been reached, but Heeger has attained 6.5 percent in his lab with a tandem organic solar cell that uses a titanium oxide layer between the two cells. This efficiency was later confirmed by the National Renewable Energy Laboratory (NREL). Yet these relatively high efficiencies for organic PV already achieved may pale in comparison with efficiencies that can be attained by Heeger and researchers at Konarka in the future. The triumph for Heeger and other solar researchers is that the multiple layers of the tandem organic solar cell could be successfully disbursed on top of one another using a printing process. Other improvements have also been made including attainment of 100 percent quantum efficiency. This means every photon absorbed by the solar cell gives an electron hole pair that allows light to be converted into electricity much more efficiently. "I see a technology pathway to 15-20 percent, and it's real, we've demonstrated all of the pieces of it," said Heeger.

Organic solar cells are flexible, light weight and can be made transparent to be used in windows for urban buildings

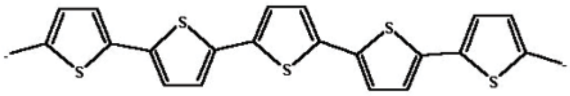


Figure 17.2 Polythiophene

Heeger and researchers from Université Laval in Quebec City, Canada are collaborating with Konarka to develop organic solar cells from a new class of photoactive polymers known as polycarbazoles (PCZ), an efficient electrical conducting polymer made from joining together carbazoles (Fig. 17.3). Polycarbazoles have been used in efficient organic LEDs and also have potential as an advanced thermoelectric material to generate electricity from heat [3] (for an explanation of thermoelectrics see Chapter 30 [4]).

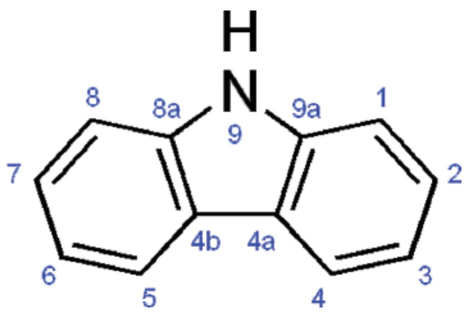


Figure 17.3 Carbazole

Konarka is moving towards the capacity to manufacture enough organic solar cells to generate 1 GW per year. More recently they announced 6.4 percent efficiency for their single junction solar cells certified by NREL. These solar cells are still at an early stage, but are expected to be ready for production within 12-18 months. Konarka's solar cells are manufactured using large scale ink-jet printers or coating equipment, originally used for film processing. This produces cells at one-tenth the cost of conventional silicon solar cells.

The polymers used to make organic solar cells are made from petroleum. In the wake of peak oil and an impending energy crisis, oil pumped from the earth should be used to build the infrastructure of sustainable energy systems, especially organic solar cells. "One thing we should not do with oil is burn it, it's valuable as a producer of all kinds of chemicals for our lives, everything from pharmaceuticals to the solar cell," said Heeger. For the future, it is also possible to get the carbon molecules needed to make solar cells from renewable resources such as biomass.

There are still obstacles for organic PV to become mainstream. Most organic solar PV companies including Konarka, though confident about the longevity of their solar cells, are uncertain as to actually how long they will last. One method for increasing the lifetime is to encapsulate the solar PV material to protect it from adverse conditions, including possible over heating from the sun. Studies by researchers at Konarka so far show that their organic solar cells last for one year when exposed to rooftop conditions in the Eastern US [5]. Materials for encapsulating organic solar cells include glass, which Konarka has found to be one of the best barriers yet, and is optimistic about accelerated test results in the near future.

According to Rick Hess, CEO of Konarka, recent accelerated lifetime tests that expose the solar cells to 65˚C in the dark, 65˚C under one sun and 85 percent relative humidity, show that cells produced by Konarka last 3-5 years. Konarka is also testing the lifetime of proprietary materials that it cannot reveal due to competitor interest. These materials have a lifetime of 10 years, but are not yet in sufficient quantities for commercial scale production. "Our main goal is improving the efficiency and lifetime of the material," said Hess. Once Konarka obtains an organic solar cell that has a lifetime of 10-15 years and an efficiency of 10-20 percent, "then it's a revolutionary technology and has many advantages," Heeger said. Until then, Konarka will continue to focus on the off-grid market such as portable applications. With the continued increase in solar cell efficiency and lower costs, the rooftop PV market may not be far off for organic solar cells. In the near future, Konarka will not be the only company manufacturing affordable third generation solar cells. Organic solar cells and DSSCs (dye sensitised solar cells) are already being developed by researchers and solar companies in the UK.

SOLAR CLOTHES & SUN POWERED LAPTOPS

One of the most recent advances in solar PV technology are hybrid (organic/inorganic) solar cells that use a dye to convert light across the solar spectrum. DSSCs absorb light similarly to photosynthesis in plants. They are mounted onto glass substrates, could be used virtually anywhere, and can be made from take-home kits. But there are still obstacles to overcome to improve their efficiency and functionality.

The solar entrepreneur G24 Innovations is currently at the 'beta' stage of development, but in its 30 MW capacity 'roll to roll' manufacturing plant built in Cardiff, Wales, in the UK, already making DSSCs that they plan to sell around the world. As DSSCs can be used virtually anywhere there is light, they have a wide variety of applications for portable and small scale power production, including LED lighting in developing countries. Some of their products can actually be worn on the body to provide solar power for small electronic devices. G24 Innovations says they will be the first producer of solar cells to rely entirely on renewable sources of energy, leading to drastic reductions in greenhouse gas emissions.

G24 Innovations is one of two third generation solar companies to benefit from working closely with the inventor Dr. Michael Grätzel who has produced the highest efficiency DSSCs to date in his lab at Ecole Polytechnique Fédérale in Lausanne, Switzerland [1]. Grätzel's electrolyte solar cells have reached efficiencies over 11 percent with an electrolyte DSSC, while solid-state DSSCs have an overall efficiency of 5 percent.

The higher efficiency electrolyte DSSCs may not , however, be the best option due to defects such as solvent evaporation and leakage [6].

Improvements in solid state cells have been made using an 'ion-coordinating structure' with a ruthenium dye, K51 similar to dye Z907 [1]. Cells that use the K51 dye have higher voltages overall because it suppresses charge recombination. Organic dyes used in solid state DSSCs have resulted in a significant increase in open circuit voltage. A single junction solid state DSSC reached an open circuit voltage of 1 V and an efficiency of 3 percent [6]. This may not seem much, but it is the current record for open circuit voltage for a solid state DSSC. If this continues to improve then there is little doubt that DSSCs will be commonplace with multiple applications as they appear more stable than their electrolyte-based counterparts.

Grätzel is also working with another innovator in DSSC technology, Dyesol, based in Australia and the UK with subsidiaries in Europe and Asia. Dyesol is developing projects and partnering with multi-national companies throughout the world to manufacture DSSCs integrated into steel sheets and glass for buildings. Dyesol's manufacturing facility to produce DSSCs for steel is located in Shotton, North Wales and was developed through a partnership with UK steel manufacturer Corus, along with support from the Welsh Assembly Government. According to the CEO of Dyesol UK Andrew King, their gel electrolyte DSSCs on steel and glass substrates have efficiencies between 6-12 percent and have come close to reaching a target lifetime of 20 years based on accelerated lifetime tests. The DSSC plant in North Wales is expected to be fully operational in November 2009 and will begin manufacturing and evaluating its DSSC steel roofing panels. King says one of the attributes of manufacturing DSSCs vs. conventional solar cells is that they have low embodied energy and can be scalable up to millions of square metres per year. Dyesol is also working with other partners to apply DSSCs in glass awnings and facades and to deliver DSSC products to the Asian market.

NEW COLLABORATIVE RESEARCH

Universities throughout the UK have come together to investigate the underlying function of DSSCs and organic solar cells that should lead to more efficient devices over time. The SUPERGEN Excitonic Solar Cell Consortium is a group of top university scientists focusing on the development of affordable, efficient dye sensitised and organic solar cells.

James Durant, professor of photochemistry at Imperial College London and member of SUPERGEN, recognizes the need for collaboration between researchers from different fields to develop third generation solar cells. DSSCs commercialised today use ruthenium polypyridyl dyes and are titanium oxide based. They function in a similar way to photosynthesis in plants due to the redox (reduction-oxidation) reactions of the electrolyte of the cell. Redox reactions are found throughout nature in a variety of physical and biological processes from cellular respiration to energy storage, making research in artificial photosynthesis all the more valuable for harnessing solar energy (see Chapter 27 [7]). Ruthenium has also been used recently to break down water into hydrogen and oxygen using sunlight to produce clean burning fuel (see Chapter 29 [8]).

As DSSCs can be used virtually anywhere there is light, they have a wide variety of applications for portable and small scale power production, including LED lighting in developing countries. Some of their products can actually be worn on the body to provide solar power for small electronic devices

DSSCs that use polypyridyl dyes are the most efficient and therefore favoured by industry. But "they're not the cheapest in the world," said Durant, "there is much more to the development of the dye cells than the dyes." Durant gives the example of changing the substrate of the cells: "The point is that simply changing from glass to a different substrate you end up having to change all of the different components of the cell to get the best performance." There is often a compromise between cost and efficiency with solar cells, especially third generation solar cells where the object is to make them as cheap and as efficient as possible. The DSSCs manufactured by G24 Innovations have only 3 percent efficiency, but are far more stable and cost effective.

Durant and his research team at Imperial College have also published widely on organic solar cells. One of their most promising discoveries is the effect of thermal annealing on some of the polymers used in plastic solar cells. Thermal annealing is done by heating materials above their re-crystallisation temperature, and increasing the efficiency of solar cells using fullerene blend films. For example, 6,6-phenyl C61-butyric acid methyl ester (PCBM) (fullerenes) and poly(3-hexylthiophene) (P3HT) (Fig. 17.4), can be heated at 140 ˚C for a short period of time for thermal annealing. Organic solar cells made from these blends have reported efficiencies in excess of 4 percent. Thermal annealing changes the oxidation potential of the polymer when it is crystallised and provides more energy to drive the charge separation [9]. It also changes the nanomorphology of the solar cell, making it "less likely for generated holes and electrons to bump into each other." This discovery could be of benefit to organic solar cell companies such as Konarka that are commercialising solar cells using fullerene polymers. Another material used to achieve efficiencies above 5 percent is poly[4,4-bis(2-ethylhexyl)cyclopenta[2,1-b;3,4-b′] dithiophene-2.6-diyl-alt-2,1,3-benzothiadiazole-4,7-diyl] or PCPDTBT. When blended with PCBM, a white-light power efficiency of 5.5 percent was achieved and no obstacles are foreseen in developing organic solar cells well beyond this efficiency [9].

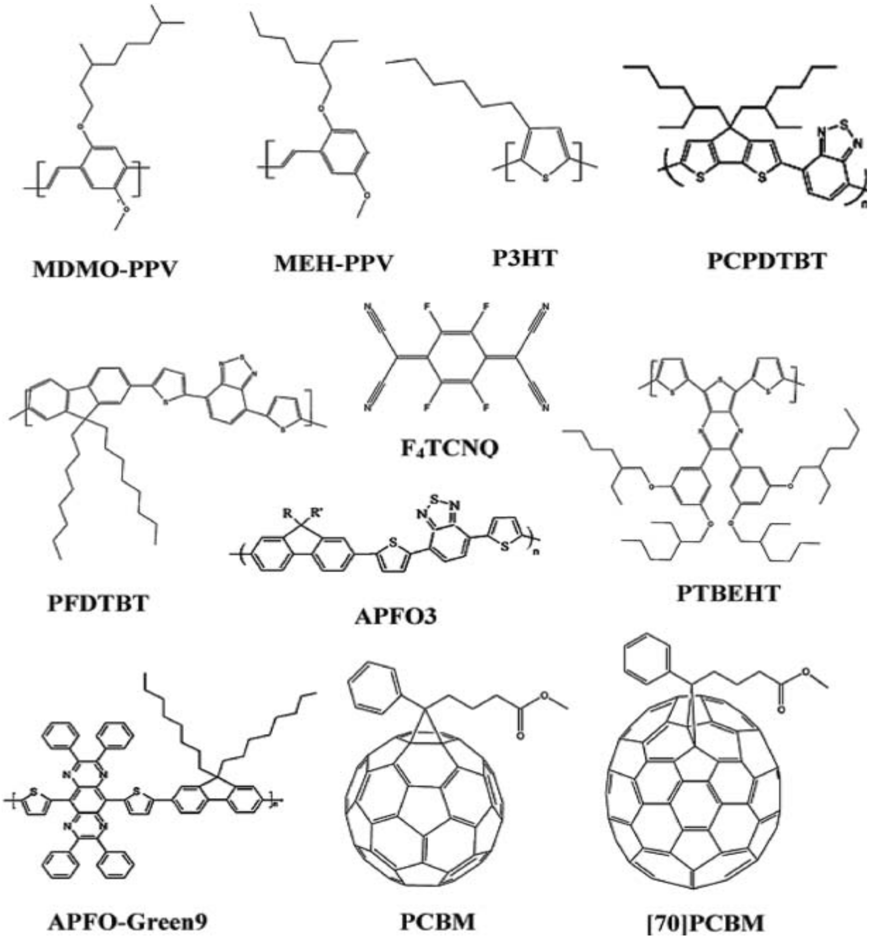


Figure 17.4 A variety of different families of polymers are used for organic solar cells

NANOTECH HYBRID ORGANIC SOLAR CELLS

Nanotechnology continues to influence the solar industry bringing forth its promising advances in the case of quantum dots, nanoparticles that could greatly increase the efficiency of organic solar cells by releasing multiple excitons [1] and nanotubes that if applied could also result in high efficiency organic PV, but could also be putting public health at risk if unregulated [10].

Earlier this year, the Advanced Institute of Technology (ATI) at the University of Surrey received €1 million from the German energy corporation E.ON to develop a highly efficient organic solar cell of 10 percent efficiency or more, along with research in energy storage and production. A team of researchers at ATI are using carbon nanotubes to boost the efficiency of existing organic solar cell materials to make organic PV available to a wider market.

ATI use multi-walled nanotubes, principally because they are highly efficient conductors and cheaper than single-wall carbon nanotubes. Multi-walled nanotubes for applications in organic PV tend to be less than 20 nm in diameter, as the thickness of the organic solar cell itself is less than 200 nm. The organic solar cells are called "bulk hetero junctions", and refer to two different materials interlaced with each other in order to create interfaces with the bulk of the polymer material. Dr. Ravi P. Silva, director of ATI and head of Nano-Electronics Centre at University of Surrey, says they have improved on a number of aspects of bulk hetero junction organic solar cells, especially the process of dispersing inks in manufacture. "Our strategy in this program and within the group is to improve on the transfer of the inks onto surfaces over large areas such that they become something that is more commercially viable," said Silva. One of the biggest problems with using nanotubes in organic solar cells is that they are hydrophobic and clump together when being dispersed due to poor solubility [11]. "One of the tricks we have learned is to de-clump [the nanotubes] in such a manner that you have this very nice distributed network on the inks," said Silva.

Multi-walled nanotubes consist of not more than 1-2 percent by weight of the material used for the organic solar cells developed at ATI. According to Silva, the carbon nanotubes might have conductivity a thousand fold greater than the polymers and molecules used to make the cells themselves. "Essentially what the carbon nanotubes do is create superhighways for charge to disassociate and go to the two middle contacts on either end [of the cell]," he said. They are capable of carrying current densities 2-3x that of copper [11]. Multi-wall nanotubes also have a thermal conductivity 5x higher than that of copper, so they can endure high temperatures, and potentially be used with concentrated light. Multi-wall nanotubes have also demonstrated efficient multi-photon absorption of infrared light [11]. However, problems still remain with longevity as degradation of organic solar cells results from exposure to UV light and heating. "If you can get rid of the heat fast enough it means that you have a material that can last longer," said Silva. Heat is a problem faced by solar researchers working on all generations of solar PV technology as solar cells generate electricity from photons, not thermal energy.

Another advantage in using organic materials is they can be wrapped around multi-wall nanotubes to help isolate their conductive paths and also help the organic hybrid solar cells absorb light well outside the visible range of the electromagnetic spectrum. Organic solar cells, such as Heeger's tandem organic solar cell and solar cells produced by Konarka already absorb infrared light, and are currently improved to increase their light harvesting capability. Silva says multi-walled nanotubes could increase the efficiency of organic solar cells beyond 10 percent because they introduce so many other improvements. "The key is whether they stack up when you put together a device, so far experimentally, we can improve on 25 percent of every aspect separately," said Silva.

FIND NEW SOLAR PARTNERSHIPS

One of the goals of ATI is to work with existing organic solar cell companies to improve on the materials they are currently using for their solar cells. "What we would like to do is get some proprietary material and modify it, because what we are effectively doing is providing new types of inks, we need to learn how to disperse carbon nanotubes effectively in materials," said Silva.

Silva says ATI has been visited by a variety of interested parties from around the world to see the potential improvements their designs could give to the organic solar PV industry. Silva would like ATI to form a business partnership with organic solar PV companies, such as Konarka, in order for them to utilise the technological improvements they have made so far. But there are difficulties involving companies' intellectual property that need to be sorted for innovations to impact the market. "Many companies have their own proprietary solutions, now this is the biggest issue here, what are the technologies available for outside use?" said Silva. According to Hess, Konarka does see potential in improving their solar cells using nanotubes and would be interested in working with research groups in the future to develop hybrid organic solar cells.

THIRD GENERATION SOLAR CELLS CLEANER

Life cycle analysis (LCA) [see Chapter 14 [12] of organic solar cells and DSSCs show that they have lower environmental impacts compared to conventional solar cells and the cost could also be substantially less than silicon-based solar cells if they achieve higher efficiencies. For example, if organic solar cells reach 11 percent efficiency they are estimated to cost half as much to produce ($1.54 per watt-peak (Wp)) as available multicrystalline solar cells [13]. Often referred to as simply 'watt,' watt-peak (Wp) is the unit used by the solar industry for the watt output of a solar device illuminated under ideal conditions (1 000 Watts/m² intensity passing through an air mass of 1.5 (earth's atmosphere)).

According to recent life cycle analysis of P3HT/PCBM polymer solar cells, the expected energy payback time (EPBT) is 1.26 years [13], which is considerably better than the 2.2 years for multicrystalline and 2.7 years for monocrystalline solar cells. It is closer to the 1.7 years of ribbon silicon and slightly above the 1.1 years of thin-film CdTe (cadmium tellurium) solar cells [12]. Electrolyte (liquid state) DSSCs have the lowest EPBT of all close to 0.8 years based on data from ECN Solar Energy in the Netherlands [14].

Producing polymer solar cells emits 819 g CO_2 equivalent per Wp versus 1443 g CO_2 for thin film silicon solar cells and 1559 g CO_2 for multi-crystalline solar cells, while production of DSSCs emits 590 g CO_2 equivalent per Wp [12]. DSSCs have been found to vary in CO_2 emissions from as low as 20 g CO_2 equivalent per kWh to as high as 120 g. However, replacing the glass substrate for DSSCs and polymer solar cells would reduce emissions further for both types of solar cells [13] [14]. Currently, thin-film CdTe solar cells still have some of the lowest GHG emissions at slightly over 20 g CO_2 equivalent per kWh [12]. As third generation solar cells are developed further over time they could likely have the least environmental impact of any solar cell on the market, many times lower than the highest efficiency solar cells.

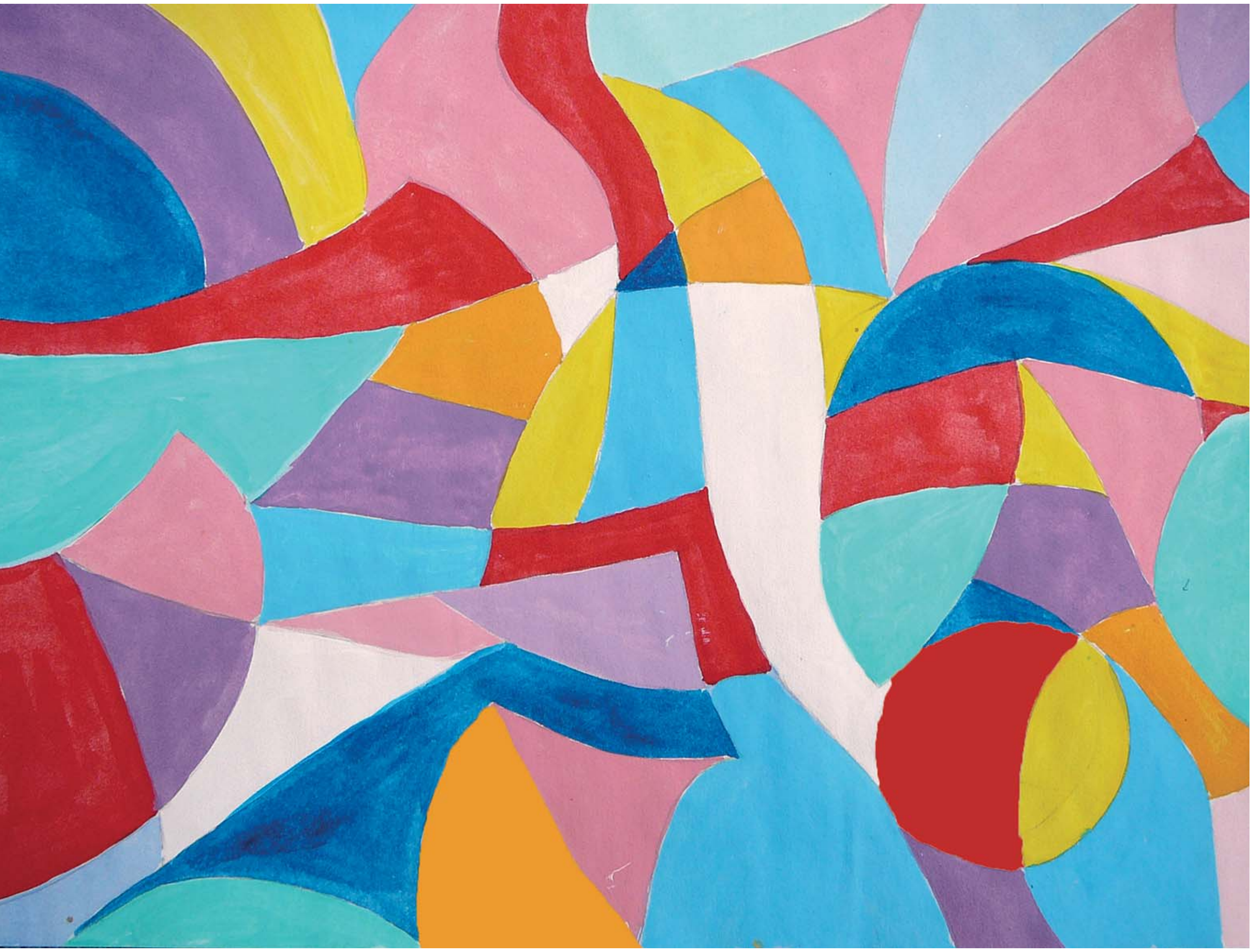
TOXICITY

ISIS has reported on a number of studies on health hazards involving single-wall nanotubes inhaled by mice and other animals [10]. Multi-walled nanotubes could also pose similar or worse health risks, as they are morphologically similar to asbestos and if inhaled could cause asbestosis. Professor Ken Donaldson at the University of Edinburgh Centre for Inflammation Research showed that manufactured nanoparticles can pose a risk to health depending on exposure pathways and the length of the nanotubes [15]. Recently, two workers in a paint factory in China exposed to nanoparticles died while seven others acquired serious lung disease that persisted after leaving the factory. The nanoparticles involved have not yet been identified [16]. According to Silva, ATI follows the best health safety advice available. However, Silva finds that actual guidelines for handling nanomaterials still need to be created. Other health concerns have also been raised for manufacturing hybrid organic solar cells such as DSSCs [1]. In order for hybrid organic solar cells to become cleaner and safer for widespread public use, potential health hazards need to be better understood and to be resolved.

18

WIND ELECTRIFIES WORLD 40 TIMES OVER

Wind could electrify the world or provide its energy needs many times over, but not necessarily with big turbines and wind farms



Wind turbine by Mae-Wan Ho

ENORMOUS POTENTIAL OF WIND POWER

Wind turbines on land could provide more than 40 times the world's current electricity consumption or over five times its total energy needs. That's the latest assessment using wind data from meteorological sources [1]. A network of 2.5-megawatt (MW) turbines on land restricted to non-forested, ice-free, nonurban areas operating at as little as 20 percent of their rated capacity would do the trick; allowing for the fact that the wind does not blow constantly. To put this into perspective, wind turbines installed in the US in 2004 and 2005 operate on average at 36 percent of rated capacity.

For the United States, the central plain states

COUNTRY	CO_2 EMISSION, MILLION TONNES	ELECTRICITY CONSUMPTION, TWH	ONSHORE	OFFSHORE
US	5 956.98	3 815.9	74 000	14 000
China	5 607.09	2 398.5	39 000	4 600
Russia	1 696.00	779.6	120 000	23 000
Japan	1 230.36	974.1	570	2 700
India	1 165.72	488.8	2 900	1 100
Germany	844.17	545.7	3 200	940
Canada	631.26	540.5	78 000	21 000
UK	577.17	348.6	4 400	6,200
S Korea	499.63	352.2	130	990
Italy	466.64	307.5	250	160

Table 18.1 Wind power potential for the 10 biggest CO_2 emitting countries

could accommodate enough wind turbines to provide as much as16 times the country's total present demand for electricity.

Wind power is on a steep ascent. It accounted for 42 percent of all new electrical capacity added to the US in 2008; but it is still only a tiny fraction of the total capacity, 25.4 GW out of 1 075GW. The Global Wind Energy Council projected a 17-fold increase in wind-powered generation of electricity globally by 2030.

SIMULATING GLOBAL WIND FIELDS WITH BEST DATA

Xi Lu and Michael McElroy at Harvard University, Cambridge Massachusetts in the United States and Juha Kiviluoma at the Technical Research Centre of Finland based their study on a simulation of global wind fields from version 5 of the Goddard Earth Observing System Data

Assimilation System (GEOS-5 DAS) that includes global meteorological data from a wide variety of sources including surface and sounding measurements, measurements and observations from aircraft, balloons, ships, buoys, dropsondes (radio probes dropped by parachute) and satellites; the gamut of data that can provide the world with the best possible meteorological forecasts enhanced by application of these data in a retrospective analysis.

The land-based turbines are assumed to have a rated capacity of 2.5 MW with somewhat larger turbines, 3.6 MW, deployed offshore, to take account of the greater cost of construction and the economic incentive to build larger turbines to capture the higher wind speeds available there. In siting turbines on land, the study excluded densely populated regions and areas occupied by forests and environments distinguished by permanent snow and ice cover (notably Greenland and Antarctica). Turbines located offshore were restricted to water depths less than 200 m and to distances within 92.6 km from the coast.

Optimal spacing of the turbines in an individual wind farm involves a trade off between various costs: turbines, site development, laying power cables, routine operations and maintenance. Turbines must be spaced to minimize interference in airflow and thisrequires a compromise between maximizing power generation per turbine and maximizing the number of turbines sited per unit area. For example, restricting overall power loss to < 20 percent requires a downstream spacing >7 rotor diameters, and a cross-wind spacing of > 4 diameters.

The power yield is assumed to be only a fraction (20 percent) of the maximum potential to account for the variability of the wind over the course of a year.

In this way, a world map of the annual wind power potential (W/m^2) is obtained; and the country by country potential for both on land and off shore wind power also represented.

WIND POTENTIAL WORLDWIDE

The total global potential power source for wind is estimated at 2 470 EJ (ExaJoule = 10^{18}J).

Table 18.1 gives the wind power potential of 10 countries identified as the largest emitters of CO_2 in 2005, though China has surpassed the US to be the biggest emitter in 2006.

As can be seen, wind power could supply close to 18 times the electricity consumption for China, the bulk of which, 89 percent, could be derived from land wind turbines. The potential in the US is 23 times the current electricity consumption, 84 percent supplied on land. The UK's wind potential is 30 times its electricity consumption, with 41.5 percent derived from land. In terms of wind power potential, Russia ranks number one, followed by Canada, with US in third position. Much of the wind power potential in Russia and Canada is located at large distances from population centres, however.

WIND POWER FOR THE USA

In the US, demand for electricity peaks twice a year in summer and winter separated by minima in spring and fall. Demand is greatest in summer due to air-conditioning, when it exceeds the minimum in spring/fall typically by some 25 to 35 percent. There is a negative correlation between the monthly averages of wind power production and electricity consumption. Very large wind power can produce excess electricity during large parts of the year. This allows the option of converting electricity into other energy forms. For example, plug-in hybrid electric vehicles could take advantage of short-term excesses in the electricity system, while energy-rich chemicals such as H_2 – from electrolysis of water - could provide for longer term-storage [2] (see Chapter 27).

The annual onshore wind potential on a state-by-state basis shows a high concentration in the central plains extending northward from Texas to the Dakotas, westward to Montana and Wyoming, and eastward to Minnesota and Iowa. The resource in this region could provide 16 times the total current demand in the US. As this resource is significantly larger than the local demand, it will require extending the existing power transmission grid to exploit this resource. The Electric Reliability Council of Texas, the operator responsible for the bulk of electricity transmission in Texas, estimates that the extra cost of transmitting up to 4.6 GW of wind generated electricity is ~$180/kW, or about 10 percent of the capital cost for installation of the wind-power generating equipment

Local micro-generation of wind power is eminently feasible. The cost of energy produced by small (<10 kW) wind turbine over its life time has been estimated to vary from $0.07/kWh, for a low cost turbine in a high wind area to $0.96/kWh for a high cost turbine in a low wind area

MICRO-GENERATION WITH SMALL TURBINES

The study convincingly shows that wind power can supply the world's energy use many times over; though it implies that big turbines and wind farms are necessary, which is not the case. Like solar heating and photovoltaic, local micro-generation of wind power is eminently feasible, and has been encouraged by the Ministry of Agriculture, Food & Rural Affairs in Ontario, Canada, for several years [3]. There it costs $2 000 to $8 000 per kilowatt to purchase a small wind turbine; but that represents only 12 to 48 percent of the total costs of the wind energy system, which includes inverters and batteries, sales tax, installation charges and labour. The cost of energy produced by small (<10 kW) wind turbine over its life time has been estimated to vary from $0.07/kWh, for a low cost turbine in a high wind area to $0.96/kWh for a high cost turbine in a low wind area.

In the UK, micro wind electricity generation is increasingly popular for households and commercial buildings [4]. The average UK household uses around 4 000 kWh a year, which can be produced with a 1.5 kW wind turbine. If a house is already linked to the national grid, a wind turbine can supplement the mains supply. When the wind turbine is not generating enough energy, mains electricity is used. When the turbine generates more than is needed, the excess can be exported to the national grid. A 1.5 kW wind turbine costs around £3 000 to £ 5 000 (2007 prices). The UK's Department for Business Enterprise and Regulatory Reform (BERR) runs a Low Carbon Buildings Programme that provides grants for micro-generation technologies for householders as well as public buildings [5]. The micro-generation technologies supported include solar electricity, wind turbines, water turbines (small scale hydro), solar hot water, ground source heat pumps, air source heat pumps, wood-fuelled boilers (biomass), automatic pellet-feed wood burning stoves (biomass), renewable combined heat and power, and fuel cells.

The current cost of micro wind generation is still rather high, but it could come down considerably. William Kamkwamba from a remote village in Malawi built his first wind turbine from scrap when he was 14 years old, and Max Robson in the UK has been inspired to produce for £20 an Envirocycle Scrap Wind Turbine prototype budget, that he claims cost £2 000 on the market [6] (see Chapter 18). Such low cost micro-generation options are particularly appropriate for developing countries.

Energy ball by home energy com

A CHEAP MICRO-TURBINE AT LAST?

In another development, John Gregg, an international expert in spin electronics and magnetic instrumentation at the University of Oxford has designed and built a wind turbine prototype in his mother's garden that uses a standard induction motor as a generator [7].

In an ordinary wind turbine, the rotating blades spin a shaft leading from the hub of the rotor to a generator. The generator transforms the rotational energy into electricity. The simplest generator works by electromagnetic induction to produce an electrical voltage – a difference in electrical potential – that can drive an electric current through an external circuit. Whenever an electrical conductor moves relative to a magnetic field, voltage is induced in the conductor. If a coil is spinning in a magnetic field, then the two sides of the coil moves in opposite directions, and the voltages induced in each side add up to produce a direct current (DC) through the external circuit. In order to fit in with the 60 cycles alternating current (AC) of the domestic electricity supply, an inverter is needed to convert the DC into 60 Hertz AC, and this is complicated as the voltage produced depends on the speed of the rotor, which in turn depends on the wind speed. The high costs of wind turbines are due to custom-built generators, invertors, storage batteries and complex circuitry.

Gregg struck on the idea of using an electric (induction) motor as a generator as the result of a question asked by a student: How can an induction motor work as a generator?

An electric motor uses electromagnetic induction to create motion, which is the opposite of what a generator does. It consists of an electromagnet rotating in the field of a permanent magnetic (or another electromagnet) on the simple principle that like poles repel and opposite poles attract.

In trying to answer the student's question, Gregg spotted a novel and very cheap way of using an induction motor as a generator, basically by running it backwards. Induction motors can be found in everything from domestic appliances such as washing machines to industrial machines.

The electricity generated by using an AC inductor motor is not at constant voltage or frequency. But, Gregg realises that hot-water tank heater elements don't mind variable voltages or frequencies. "That's why we can make it cheaply and why it performs well because we are not handcuffed by the necessity to deliver 249V 50 Hz," Gregg said.

Instead, Gregg designed a patented electronic control method, drawing inspiration from Swiss locomotives. Instead of a mechanical gearbox, the train changes gear electrically as the field windings on the magnet on the motor are switched to give maximum acceleration at all speeds. "Our generator works in a similar fashion," said Gregg. "Because the generator is configured as a constant power source and acts effectively as a generator and a continuous variable electronic gearbox, the turbine aerofoils operate on the peak of their performance curves at all times, and all the power they deliver is harvested and channelled to the load."

The wind turbine has a six-metre diameter blade and a standard 7.5 kW induction motor used as a generator. Because of planning permission, it cannot be sited high enough to catch the optimum amount of wind. Nevertheless, early results show the equivalent of 1 kW continuous power. The turbine provides electricity for a heat exchanger tank, which heats the domestic hot-water tank and also feed surplus heat into the domestic central heating, so saving on oil as well as the electricity bill.

Five years ago, when it all started, it would have cost £33 000 to install an equivalent commercially available turbine.

With co-inventor Mazhar Bari, Gregg is now proposing a spinout company, Renewox, though Isis Innovation, the technology transfer company of Oxford University.

"Because the generator is configured as a constant power source and acts effectively as a generator and a continuous variable electronic gearbox, the turbine aerofoils operate on the peak of their performance curves at all times, and all the power they deliver is harvested and channelled to the load."

19

HARNESSING THE WIND WITH SCRAP

A boy who had to leave school at 14 shows the world how to harness wind energy by using dumped objects

ELECTRICITY FROM RECYCLED MATERIALS

William Kamkwamba was only 14 years old when he built a windmill to provide his family home in a remote village in Malawi with enough electricity to read by and to listen to the radio [1]. William first started thinking about energy when he had to drop out of school early because his parents could no longer afford the school fees after the maize harvests failed in 2001. He got his idea from a school library book called "Using Energy" and modified a design for a windmill with materials that were to hand such as an old bicycle, broken PVC pipes, a pair of worn out shoes, copper wire and a tractor fan.

William and his wind turbine from scrap

William's motivation for his invention was the health of his sisters. At night their home would be lit with paraffin candles that emit toxic fumes similar to those from burning diese. The smoke was making his sister ill. At first his neighbours mocked him saying that he was going mad, but William persevered with the design because the book told him that it worked.

In Malawi only 2 percent of the population enjoy household electricity, so Williams' neighbours, who had no electricity at all, soon changed their minds when they heard the sound of Malawian music coming from his house. They were even happier when they realised that William's windmill could re-charge their mobile phones too.

His first attempt at a windmill gave his family enough energy to light one room so William decided to adapt the design further by adding a fourth rotor blade to create more power. He asked a local tinsmith to cut more efficient steel blades from a recycled oil drum and added a second windmill below the original blades that had been fashioned from heated, flattened and shaped PVC pipes. He also replaced the bicycle chain that doubled as a pulley rotor with an old car fan belt that worked much better.

ADAPTING TO LOCAL CONDITIONS

The new design speeded up the dynamo (electric generator), the sort that powers bicycle headlights, from generating 12 to 20 volts. This was enough to provide energy to the battery for lighting his whole house, plus two radios, two mobile phone chargers and a car battery for backup power. The windmill is atop a 12 metre tower made out of blue gum tree poles that can catch the wind high above the windy village of around sixty families. William has also experimented with a radio transmitter that can serve his local community. He plans to broadcast important HIV prevention messages as well as popular music to a 20 square mile radius [2].

William's project encountered several problems along the way. He had to improvise necessary electrical components such as light switches from the rubber off old shoes and some springs. He also needed a generator, which a friend gave him. With the help of other farmers, he found discarded scrap materials on the tobacco plantations in his locality.

Since building his windmill William has been made a Fellow of TEDGlobal, a not for profit conference that brings together exceptional people from around the world who specialise in Technology, Entertainment and Design (TED). In his conference speech in Tanzania in 2007, William said, “When I dropped out of school, I went to the library and read and gathered information about how to make a windmill. And I tried, and I made it.” [3].

William was flown over New York in a helicopter; visited wind farms in the USA, exhibited at the Museum of Science and Technology in Chicago; wrote a book about his windmill [4]; was the subject of an award-winning short documentary film [5]; and set up a blog about how he harnessed the wind to produce a reliable source of electricity for his community [6].

Supporters in his native country are impressed with the actions of a boy who did not blame his parents, the power companies, the government, or policy makers for his lack of education. William simply got on with the task in hand. His efforts have resulted in his addressing the World Economic Forum Africa in 2008, where he dined with the President of Malawi. At the 2009 TEDGlobal conference in Oxford, the young inventor, now 21 years old, gave a lecture about his experiences so far.

BACK TO SCHOOL

William’s story has attracted interest around the world and through TED he has been given financial help to improve his project by incorporating solar energy. This expanded system has allowed him to add a deep-water well that pumps water to irrigate crops in his native Mastala village in Kusungu district. His next project is to re-design a new classroom for his local school, which has no lighting or water.

Through the interest garnered by a Malawi’s Daily Times article entitled, “School Drop-Out with a Streak of Genius” and the University of Cape Town as well as TED, William was sponsored to return to secondary school after five years’ break and has completed his studies as an electrical engineer at the African Leadership Academy in Johannesburg. His next step is to start a windmill company and to teach.

THE ENVIRONMENTAL SCRAP WIND TURBINE

This success story may also have acted as catalyst for a more recent project at Portsmouth University [7]. Max Robson, a 22 year old graduate has created a wind turbine from recycled materials found at the roadside and in front gardens. The “Envirocycle Scrap Wind Turbine” prototype converts kinetic energy from the wind into 73 Watts of electricity which can then be stored in a battery. When fully charged the battery provides energy for 63 hours of lighting and 30 hours of radio [8].

This research project was privately funded so that small scale turbines can be used around the world. Meanwhile, Portsmouth University is funding Max through a postgraduate Masters Degree to develop the project using the University’s resources. So far two primary schools have invested in the educational pack that Max has produced so that schools can build their own turbines and learn about renewable energy. One school is running a laptop off their turbine and the ultimate aim of the research is to link with the schools in the developing world that are also producing energy from scrap turbines.

Max Robson’s windmill cost him £20 to produce and is 1.8 metres wide, so it is low cost and low impact on the surrounding environment. It can be constructed in a matter of days using hand tools. Max points out that the nearest alternative wind turbine on the market costs £2 000.

Max’ Envirocycle Scrap Wind Turbine

Max Robson’s windmill cost him £20 to produce and is 1.8 metres wide, the nearest alternative wind turbine on the market costs £2 000

For example, Micro Wind Turbines that have been used for decades on boats have been adapted for household use and are springing up on UK urban rooftops. These mini turbines supplement national grid electricity and cost around £1 000 after grants, or £1 500 fully installed from a high street DIY store, which can save the homeowner around 30 percent on electricity bills per year. Another, even cheaper micro-wind turbine can be used to charge batteries with electricity. These cost around £800, but also require the cost of a power inverter to convert 12 or 24 DC volts (V) into 240 AC V as well as a bank of suitable batteries [9].

Max and William have demonstrated that ingenious, alternative and affordable local solutions to small-scale electricity needs can be made by using relatively easily found scrap for a global renewable future.

20

KENYA TO BUILD AFRICAS LARGEST WINDFARM

Ambitious plans to light up Africa, but local off grid power sources must not be neglected

Lake Turkana

A CLEAN ENERGY FRONTIER

The desert land around the beautiful Lake Turkana in Kenya, the scene of an award winning film [1] is set to become the site of Africa's largest wind farm by 2012. This ambitious project aims to end Africa's electrical blackouts and tackle global warming simultaneously [2].

The Lake Turkana Wind Project (LTWP) has received €300 million, 70 percent of total cost, from the African Development Bank; the remainder will come from private Dutch and Kenyan investors. The project will produce 310 MW of power going directly to the national grid. It is hoped that this will meet the surging demand for energy though renewable resources.

The African Development Bank is a treaty signed in 1963 [3] which focuses on regional development and is active in 78 countries throughout the Continent. Its aims are to:

- Make loans and equity investments for the social and economic advancement of regional member countries
- Provide technical assistance for the preparation and execution of development projects and programs
- Promote investments of public and private capital for developing purposes
- Assist in co-ordinating national and multinational projects and programs that promote regional integration.

The LTWP consists of 365 wind turbines each 30-40 metres tall, with a capacity of 850 KW. This will add approximately 25 percent to Kenya's existing electricity capacity, which is projected to produce 1 440 GWh of energy per year, enough to light up around 2 million Kenyan households [4].

Currently, less than one Kenyan in five has access to electricity and almost three quarters of its major supplier KenGen's electricity comes from hydropower. Another 11 percent comes from geothermal plants that absorb heat and steam from rocks deep below the Rift Valley. But low rainfall in the country has boosted the short term reliance on fossil fuels such as coal. However, as only 9 percent of Kenya's total energy comes from electricity (see Table 20.1), this project is a significant step towards Kenya's 2030 Vision of Development and Least Cost Power Development Plan (2009-2029).

AFRICA GOING FOR THE WIND

Kenya is not the only African country harnessing energy from the wind. The Tigray region of neighbouring Ethiopia, which has already produced remarkable crop yields from compost [5], has recently commissioned a £190 million 120 MW wind farm. This will represent 15 percent of Ethiopia's current electrical capacity and more wind farms are planned. In Tanzania, 100 MW of power will be produced from two projects in the Central Singida region, which account for more than 10 percent of the current supply.

Earlier in 2009, South Africa became the first African country to announce a feed-in tariff for wind power, which means that customers generating electricity receive a premium for selling power to the national grid.

Two further wind projects are underway in Kenya. One is in the popular tourist town Naivasha and one is in the Ngong Hills near Nairobi where the Danish wind company Vestas has already installed six 50-metre V52 turbines contributing 5.1 MW to the national grid. It is believed that 365 V52 turbines will be used in the LTWP.

THE TURKANA CHANNEL JET

The LTWP will be constructed at a rate of one turbine per day starting from July 2011 to be completed by July 2012. The wind park will take advantage of the low level jet stream called the Turkana Channel Jet that blows all year round and is at full force during the night. The average monthly wind speed at the site, on the southeast side of Lake Turkana is 11 metres per second (at a height of between 40 and 80 metres) one of the highest averages recorded globally.

The wind park will cover 40 m^2 and turbines will span three ridges 70 metres apart between 450 metres at the lake shore and the bases of Mount Kulal (2 300 masl)) and the Mount Nyiru range (2 750 masl). This is a strategy to catch the SE winds blowing through the Rift Valley in between the East African and the Ethiopian Highlands.

CARBON AFRICA

Carbon Africa is a carbon credit trading company in Kenya that has emerged in tandem with the LTWP. A carbon credit is a permit approved by a body of the United Nations (UN) known as the Clean Development Mechanism (CDM), an arrangement under Article 12 of the Kyoto Protocol. This permit allows the holder to emit one metric tonne of carbon dioxide or carbon dioxide equivalent per credit.

Carbon credits are awarded to countries, or entities, that reduce their greenhouse gas emissions (GHG) to below a set baseline. It is expected that the LTWP will generate somewhere between 565 920 – 1 264 320 GHG emission reductions per year. Therefore, an average of 850 000 tonnes of CO_2 equivalent electricity generated from wind priced at €10 per tonne would accrue €8 500 000 per year. An independent Gold Standard review, done by an independent carbon credit certification body, will monitor the sustainable benefits of the LTWP.

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DEVELOPMENT PROS & CONS

An environmental and social impact assessment (ESIA) of the LTWP has been done [6]. The report concludes that there will be a number of social, economic and environmental impacts both positive and negative for local communities and for the region in general. For example, 196 km of new tarmac roads must be built to transport the 8 ton axle weight of each wind turbine mast and blade from Mombasa to the Lioyangalani location. There will also be the sinificant reconstruction of existing roads and the construction of a 266 km transmission line to junction electricity via multiple towns in the region to connect to a terminal substation for grid feed-in.

Currently, all the local institutions such as schools, hospitals, missionary stations and tourist facilities are powered by diesel. The Lioyangalani district is very poor, has a low nutrition rate and is dependent on food relief. Therefore, there are obvious benefits for health, education, local employment, and the stabilization of electricity supplies as well as the diversification of power sources.

ENERGY SOURCE	PERCENTAGE OF TOTAL ENERGY
Wood/Biomass	68
Petroleum	22
Electricity	9
Other sources	1

Table 20.1 Energy use in Kenya

As the bulk of Kenya's energy derives from wood fuel and other biomass resources (see Table 20.1 [6]) the result has been the highest deforestation rates in Africa.

On the negative side, a predicted 600 people working in the area at the peak of construction will increase the exploitation of natural resources, noise, vibration, pollution and risk of disease from outsiders coming in. It will also increase disease vectors from stagnant waters in pits, ponds and quarries. There will be disturbance to livestock, loss of trees, shrubs and grasses, and increased soil erosion from digging and turbine installation. There are further concerns for environmental impact on birds, fish and wildlife (see Box 20.1)

The indigenous population around Lake Turkana include four major Kenyan tribes people; the Samburu, the Turkana, the El Molo and the Rendile. According to the ESIA, they will benefit directly from cold storage for fish caught on the lake and many problems including 'relief dependency syndrome' will be solved. The EISA's table of environmental parameters has predictably placed the stabilization of electricity at the top as highly positive and the risk of bird mortality at the bottom as moderately negative. The risk to collision between birds and turbine blades is also thought to be low.

LOCAL POWER DEVELOPMENT

It must be remembered that no more than 20 percent of Africans have access to electricity, in some areas as few as 5 percent, dropping to 2 percent in rural regions [8]. Dr Bhattacharyya from Dundee University is leading a research project into energy for less-industrialised countries. He has warned that inefficient energy technologies used by low-income families in Africa such as burning wood and other biomass such as dung, crop wastes, kersosene and candles are bad for the environment and for human health, and recommends the development of local ideas.

He said, "Just extending the grid does not help the poor as they always lose out when there are shortages. What they need is local power." Therefore, off grid local and small-scale reliable power sources such as the innovative windmill made entirely from scrap materials by a boy in Malawi [9] (see Chapter 18) must be encouraged. Low or no cost strategies such as scrap turbines can help communities to power their homes and schools, to irrigate crops and to lower carbon emissions throughout the Continent.

Box 20.1

THE BEASTS, BIRDS AND FISHES OF LAKE TURKANA

Lake Turkana is in the Great Rift Valley, 400 km from Nairobi [7]. It is a saline body of water that originally flowed into the Nile, but was cut off millions of years ago. It is the 20th largest lake in the world and home to at least 84 species of birds native to Kenya. Birds such as common and wood sandpipers, African skimmers, little stints, white necked cormorants, the greater flamingo and Heulins Bustard flock there. It is a key stopover site for birds on migration passage for breeding, feeding and nesting that are supported by plankton masses in the lake.

Fish such as the African perch, tilapia and African tetra are abundant in Lake Turkana. It is also home to Africa's largest population of Nile crocodiles. While animals such as kudu, oryx, zebra, gazelle, giraffe and buffalo outside the Marabit National Park and other national parks in the region have been hunted to extinction, reptiles such as adder cobra, lizard viper and scorpion thrive.

The once abundant acacia tree has been exploited for firewood and for income generation from charcoal. Other plants in the locality are traditionally used for medicinal purposes are also eaten by the grazing herds belonging to local tribes peoples, who are mainly pastoralists.

Lake Turkana is the 20th largest lake in the world and home to at least 84 species of birds native to Kenya. It is a key stopover site for birds on migration passage for breeding, feeding and nesting that are supported by plankton masses in the lake. Fish such as the African perch, tilapia and African tetra are abundant in Lake Turkana. It is also home to Africa's largest population of Nile crocodiles

"MBWA KALI" photograph by Sam Burcher

21

BIOGAS POWERS CHINA'S ECO-ECONOMY

Biogas from biological wastes prevents carbon emissions and environmental pollution; it is powering China's burgeoning eco-economy and set to grow

Searching for a home by Li Poon

WHAT IS BIOGAS?

Biogas is a combustible mixture of gases produced by micro-organisms when livestock manure and other biological wastes are allowed to ferment in the absence of air in closed containers [1]. The major constituents of biogas are methane (CH_4, 60 percent or more by volume) and carbon dioxide (CO_2, about 35 percent); but small amounts of water vapour, hydrogen sulphide (H_2S), carbon monoxide (CO), and nitrogen (N_2) are also present. The composition of biogas varies according to the biological material. The methane content of biogas produced from night soil (human excreta), chicken manure and wastewater from slaughterhouses sometimes could reach 70 percent or more, while that from stalks and straw from crops is about 55 percent. The concentration of H_2S in biogas produced from chicken manure and molasses can be as high as 4 000mg/m^3, and from alcohol wastewater even higher at 10 000 mg/m^3. Biogas is mainly used as fuel, like natural gas, while the digested mixture of liquids and solids 'bio-slurry' and 'bio-sludge' are mainly used as organic fertiliser for crops. But there are numerous other uses for biogas, bio-slurry and bio-sludge in China.

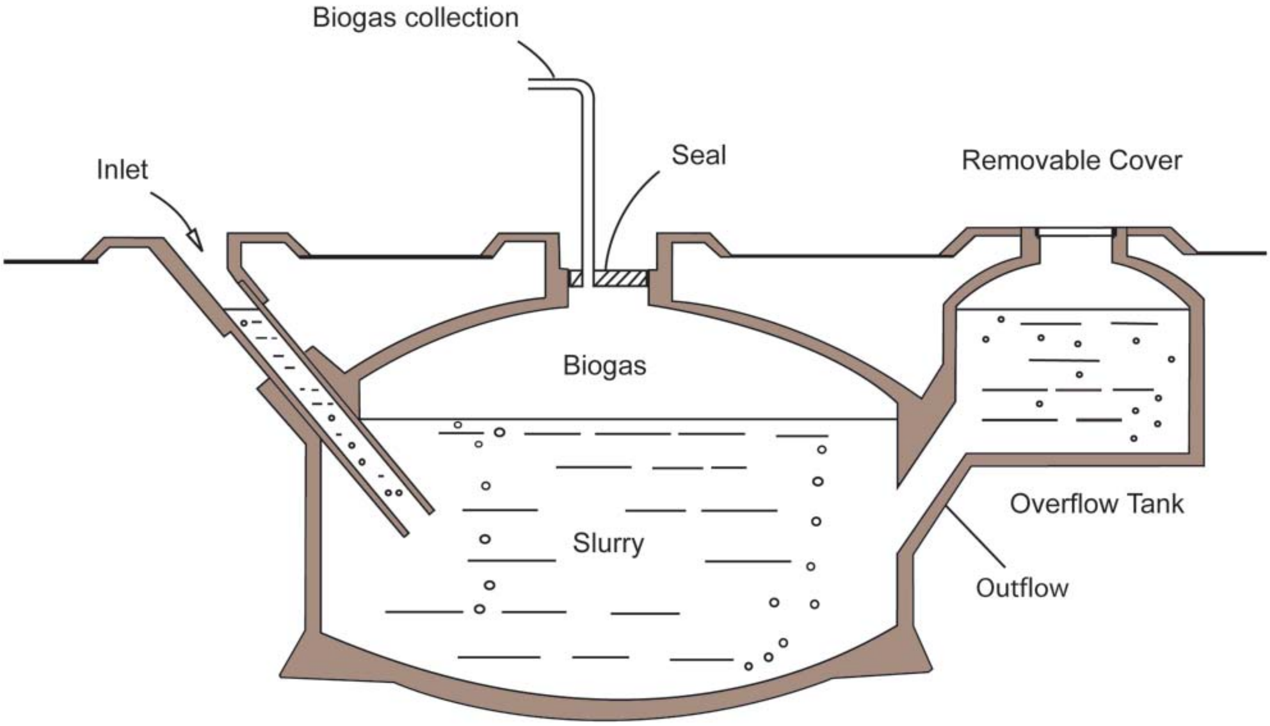

Figure 21.1 China dome digester

BRIEF HISTORY

There's evidence that biogas was used to heat bath water in Assyria during 10 BC; and the first digestion plant to produce biogas from wastes was built in a leper colony in Bombay India in 1859 [2].

China used biogas technology early in its history. By the end of the nineteenth century, simple biogas digesters had appeared in the coastal areas of southern China. Mr. Luo Guorui invented and built an eight cubic metre Guorui biogas tank in 1920, and established the Santou Guorui Biogas Lamp Company. In 1932, he moved the Company to Shanghai and changed his firm's name to Chinese Guorui Biogas Company with many branches along the Yangtze River and in the southern provinces. Chinese Guorui Biogas Digester Practical Lecture Notes was published in 1935 [3], the first monograph on biogas in China and in the world. That was the first wave of biogas use in China.

The second wave originated in Wuchang in 1958 in a campaign to exploit the multiple functions of biogas production, which simultaneously solved the problems of the disposal of manure and improvement of hygiene.

The third wave occurred between the late 1970s and early 1980s when the Chinese government considered biogas production an effective and rational use of natural resources in rural areas. Biogas production not only provided energy, but also environmental protection and improvement of hygiene, and was an important aspect of the modernization of agriculture. Some 6 million digesters were set up in China, which became the biogas capital of the world, attracting many from the developing countries to learn from it. The 'China dome' digester became the standard construction to the present day (Fig. 21.1) [4], especially for small-scale domestic use. But many new types of rural household digesters have also been built based on water pressure, as for example, the plug flow auto-cycle rural digester, the up-flow small scale digester, the fender digester, and recently, the pulse flow anaerobic reactor.

China's 2003-2010 National Rural Biogas Construction Plan was announced in 2003. The proposal was to increase biogas use by 11 million to a total of 20 million households by 2005, to make one in ten farmer's households a biogas user; although the rate would reach 15 percent in some areas. By 2010, China would increase biogas-using households by a further 31 million to a total of 50 million, so the rate of use would reach 35 percent. From 2003, a government subsidy of 1 000 Yuan (about US$ 150) would be provided for each biogas digester.

According to national statistics, 26 million households in China were using biogas sources for cooking and heating at the end of 2007 [5], and that number will be 31 million by the end of 2008.

WHY USE BIOGAS?

The main reason for using anaerobic digestion, which generates biogas as a by-product, is to treat wastes. According to the government's Chinese Ecological White Paper issued in 2002 [6], the total amount of livestock and poultry wastes generated in the country reached 2.485 billion tonnes in 1995, some 3.9 times the total industrial solid wastes. These wastes are precious resources if used properly, but constitute major pollution when discharged into rivers and lakes. It is estimated that less than 10 percent of the wastewater in China is currently treated, and that 10 million ha of farmland are seriously polluted by organic wastewater and solid wastes as well.

According to the Chinese Academy of Sciences Geography and Resources China Natural Resources and Environment Data Bank, the total annual production of manure and night soil could theoretically generate about 130 billion m^3 of methane, equivalent to 93 million tonnes of coal [7]. While only 50 percent of the theoretical production can be realised in rural areas, 80 percent of the industrial wastewater can also be used to produce methane.

The COD (chemical oxygen demand, a measure of pollutant concentration) of wastewater from a distillery often reaches 40 000 mg/litre while aerobic treatment only permits COD below 1 000 mg/litre, which means the wastewater has to be diluted 40 times. With anaerobic digestion, 90 percent of the pollutants can be readily removed, thereby greatly reducing pollution to farmland, rivers and lakes [3].

During the 10th Five Year Plan, the government invested 35 billion Yuan to promote an ecological model based on biogas. It devoted great effort to develop 2 200 biogas engineering projects for wastes from intensive animal husbandry and poultry treating more than 60 million tonnes of manure a year. In addition, it installed 137 000 digesters to treat sewage [8].

The second main reason for anaerobic digestion is that methane is a major greenhouse gas, second to carbon dioxide in amount generated, but with a global warming potential 22 times that of carbon dioxide. Using biogas not only removes polluting wastes, but also mitigates global warming [9]. The methane flux from exposed slurry is 3.92 mg per square metre per hour, compared with 10.26 mg per square metre per hour from compost in rice fields [3]. Methane mitigation saves carbon emissions and can be traded as carbon credits under the Clean Development Mechanism of the Kyoto Protocol for climate change [10]. Using biogas also solves the most serious problem of energy supply in rural areas, where people traditionally forage for fuel wood in forest. A 10 m^3 digester in rural areas can save 2 000 kg of fuel wood, which is equivalent to reforesting 0.26-4 ha [7]. Africa lost 64 million ha of forests between 1990 and 2005, more than any other continent, and fuel wood gathering was a major cause of forest depletion [11].

Biogas methane provides fuel for cooking, not only saving the forests and also the women fetching and carrying heavy loads of fuel wood. Unlike firewood, biogas burns without smoke, thus also saving women and children from respiratory distress and disease [10]. Biogas can be used to generate electricity, prolonging the active hours of the day and enabling the family to engage in social or self-improvement activities or to earn extra income.

The anaerobic digester solves sanitation problems by taking in human as well as animal manure, improving home and farm hygiene and the general environmental conditions.

Finally, anaerobic digestion yields not only biogas but also bio-slurry and bio-dregs rich in nutrients, minerals and biologically active compounds that form excellent organic fertiliser for crops and fodder for pigs and fish (see below).

RICH FERTILIZER & ANIMAL FEED

The liquid and solids in the digester are a treasure trove of valuable biological resources [3]. These include major nutrients for crops such as nitrogen (N), phosphorus (P) and potassium (K), as well as trace elements that can stimulate seed germination and growth. Also present are biologically active compounds such amino acids, growth hormones, gibberelin, sugars, humic acid, unsaturated fatty acids, vitamins, cellulase and other enzymes, and antibiotics that may suppress the growth of pathogens, which benefit both plants and animals. The slurry and solids can be used as fodder for livestock and fish. The solid phase will include the micro-organisms responsible for fermenting the wastes and producing methane, which would have multiplied in the digest, constituting a rich source of protein when the digested slurry or dregs are used as fodder.

The digested slurry can be used as organic manure in the sowing season and as a source of water in other seasons. Seeds submerged in slurry germinate better and the seedlings grow stronger. Used as a spray for plants, the slurry inhibits disease and boosts yields.

The digested slurry can be used to feed fish, the dosage depending on the transparency of the fishpond (an indication of how much organic nutrient is present). It can also be fed to pigs as an additive to speed up growth and shorter the rearing period by 25 percent, saving feeds by 15 percent. When fed to broilers and layers, the slurry from cow, chicken and pig manure increased the rate of egg laying by 14 percent, 9 percent and 7 percent respectively.

The solid dregs from the digester have high levels of humic acid and can be used as a soil conditioner or as substrate for culturing mushrooms. They can also be used to culture earthworms to be fed to chickens. Chickens fed earthworms lay 15 to 30 percent more eggs [12].

MANY USES FOR BIOGAS

Biogas can be used directly for cooking and for co-generation of electricity and heat, which is especially feasible when the biogas is used at or near the site of generation.

Biogas methane can also be used as fuel for vehicles, and is the cleanest biofuel available. Cars run on biogas methane have been voted environmental cars of the year in 2005. Thousands are operating in Sweden, which has hundreds of filling stations supplied by community biogas digesters [13] (see Chapter 22).

Biogas can be used in ovens and lamps to heat greenhouses and at the same time increase the carbon dioxide concentration to boost photosynthesis in the greenhouse plants and increase yields. Experiments in Shanxi Province have shown that increasing carbon dioxide four-fold between 6 and 8 am boosts yields by 67.2 percent [3]. Similarly, a biogas lamp gives both light and warmth to silkworm eggs increasing their rate of hatching as well as cocooning compared with the usual coal heating [3].

Biogas methane can also be used to make methanol, an organic solvent and important chemical for producing formaldehyde, chloromethane, organic glass, and compound fibre [14].

Finally, biogas can be used to prolong storage of fruit and grain [3]. An atmosphere of methane and carbon dioxide inhibits metabolism, thereby reducing the formation of ethylene in fruits and grains. It also kills harmful insects, mould, and bacteria that cause diseases.

SOME NOTABLE CASES

Here are some examples of how biogas has been used in China [15]. In 1996, grain production reached 504.3 million tonnes in China. It was hard to sell the grain. Nanyang in Henan Province had 6.7 million ha of wheat crop (1 percent of wheat cropland in China), and a record yield of 9.5 tonnes/ha that year. Nanyang also had 1.5 million tonnes of shop worn grains. So, Tianguan Alcohol Factory expanded its operation to consume 1.75 million tonnes of shop worn grains/year to produce denatured alcohol as fuel for automobiles, and used the dregs of the distillery to produce biogas in a 30 000 m^3 digester, supplying more than 20 000 households or 20 percent of the population. Nanyang became a biogas city in China.

Meili village of Shaoxing Country, Zhejiang Province produces 28 000 pigs, 10 000 ducks, 1 million ducklings and 100 000 chickens each year. In 2001, they spent 1.2 million yuan to build digesters to treat 30 tonnes of livestock and poultry wastes and nightsoil. This produced enough biogas for more than 300 households plus 7 200 tonnes of organic fertilizer each year.

Hongzhi Alcohol Corporation Limited located in Mianzhu in Sichuan Province is the largest alcohol factory in south-western China, and produces alcohol for human consumption. It runs a service using industrial organic wastewater, sewage and dregs to produce biogas, paid for by industry and residents in cities, but provided free to farmers. The company also built a biogas power plant generating 7 million kilowatts per hour. The city of Mianzhu treats 98 percent of municipal sewage including wastewater from hospitals through digesters with a total capacity of 10 000 m^3. The treated water reached national discharge standards, greatly improving the environment.

BIOGAS THE BASIS OF AN ECO-ECONOMY

Up to the end of 2005, China had 17 million digesters with a total annual production of 6.5 billion m^3 biogas [16] (equivalent to 4.94 GW capacity), mostly in rural areas, with 50 million people enjoying the benefits of biogas technology. The annual production of biogas is projected to reach 25 billion m^3 by 2020. Biogas could provide energy to one quarter of households in rural areas.

Biogas is at the centre of a burgeoning eco-economy in China. As animal husbandry goes

Biogas in Mianzhu, Sichuan

intensive, there are many large or medium size livestock and poultry farms in the suburbs of cities. An example is Fushan farm in Hangzhou, with 32.47 ha paddy fields, 4 ha tea trees, 13.7 ha water shields and 7.3 ha fishponds. It also produces 30 000 laying hens, 150 000 broilers, and 8 000 pigs a year, with 15 tonnes of solid waste and 70 tonnes of wastewater discharged daily, a huge amount of pollution. But when biogas digesters are used to deal with the pig and poultry wastes, biogas energy becomes available for processing tea and heating the chicken coop, and there's fodder for fish and pigs and fertilisers for tea trees and the paddy fields, and no pollution is exported to surrounding areas [8]. This 'eco-farm' has moved to the outskirts far from the city because of its malodour, however. It is possible to use a combination of multiple micro-organisms to deodorize pig manure or chicken manure. Also, the large amounts of water in slurry could be reused to wash away wastes in hog houses as a water-saving measure.

Northern China has cold winters but sufficient sunshine. Digesters do not operate below 10˚C, and pigs raised in winter eat but do not fatten. People also lack fresh vegetables in winter. All these problems are solved with a four-in-one eco-model that provides a greenhouse to plant vegetables, a shed to raise pigs, a digester underneath the pig shed and a toilet in the big green house adjoining the pig shed [3]. The pigs grow well with manure flowing into the digester together with human excreta. The digester works well because the temperature can be kept above 10˚C, and it greatly improves the living conditions of farmers. The digester provides biogas as energy, slurry and dregs as fertilisers, and the pigs produce carbon dioxide to enrich the greenhouse to produce plenty of quality vegetables.

In southern China, a five-in-one model incorporates pigs, digester, fruit orchard, light trap, and fishponds [3]. The pig manure flows into a digester to be fermented. Biogas is harvested to provide energy for cooking and lighting. The digested slurry is used as fertilizer for the fruit gardens and feed for pig and fish. The light-trap hangs above the fishpond to attract and kill pests, which become additional fish feed. This model is practised especially in Guangxi Province in southern China, where a yellow sticky board (a kind of fly paper) is hung in the orchard for additional pest control [17].

CONSTRAINTS & PROSPECTS

China is building new socialist villages in its current 11th five-year plan. The guidelines are to develop production and to clean the environment, to innovate to save resources. Developing biogas fits in well with this programme. The major constraint is the lack of technical capacity for running and maintaining the biogas digester.

However, a new breed of biogas farmer workers has appeared. For example, Mr. Liu Zijian in Guangxi Province has been playing a major role in his village. Liu first built an eight cubic metre digester and renovated the toilet, pigsty and kitchen at the same time, saving 7 540 Yuan (~US$ 1 100). He has worked out effective ways of getting the digester to start producing methane, and how to ensure success. Indeed, he has built 130 digesters without a single failure. The whole village has 165 digesters serving 72 percent of villagers. Nevertheless, any improvement in the design of biogas digesters to make installation and maintenance easier will encourage wider uptake.

BIOGAS TRANSFORMING RURAL CHINA

Anaerobic digestion has been transforming rural China. After 5 years of research, the Ministry of Agriculture and Asian Development Bank (ADB) initiated its Efficient Utilization of Agricultural Wastes Project in 2003 [5]. The ADB offered US$ 33.1 million in loans targeting rural Shanxi Hubei, Henan and Jiangxi provinces. With $8.2 million in ADB loans, the Shanxi provincial authority also allocated $8.1 million in matching funds along with a $841 000 grant from the Global Environment Fund (GEF). The ADB programme with its supporting funds focussed on 1 685 projects combining biogas digester, greenhouses, vegetable growing and livestock operations. Another 3 500 projects combined biogas production, vegetable growing and livestock operations. In addition, 6 large-scale biomass projects were planned.

Farmers received loans equivalent to half the construction costs, said Liu Wenyong, deputy director of the Shanxi Rural Energy Office, with repayment schedules based on the income levels and living conditions of the farmers. Farmers were also given technical support and training to ensure that the biogas facilities are sustainable.

“Through the ADB biogas projects, we trained more than 9 000 people including 8 000 farmers and 300 biogas facility experts, construction workers and management staff,” said Liu.

“The greatest achievement is that more than 60 percent of the trainees are women, as women are the main users of biogas for cooking and other purposes in their homes,” Liu added.

Xinxing Co in Jiaochen country received a US$ 200 000 ADB loan to build a new pig farm, scheduled for completion in 2010. A nearby biomass plant will process pig dung to produce biogas. The farm’s production capacity will increase from 2 200 pigs to about 9 000 animals. “So far, 100 households near here are using biogas produced by the pig farm without any charges to them,” said Ren Jianguan, an agricultural officer of Hiaocheng county.

The company plans to support the energy needs of more than 300 households once the larger pig farm is fully operational. In future, the energy from the farm will be priced at 1.2 to 1.5 yuan per m^3, which is still cheaper than burning coal.

According to the ADB, the programme will ultimately benefit about 34 080 household in the four selected provinces. The potential environmental benefits include a reduction in CO_2 emissions of about 78 388 tonnes per year, or more than 1 million tonnes over the life time of the programme.

Over the past five years, China has invested more than 10.5 billion yuan in government bonds for construction of biogas projects in rural areas, including 98 600 villagers

By the end of 2008, an estimated 31 million households were using biogas for heating and cooking. This is equivalent to 9 GW of renewable energy.

Hong Fuzeng, an agricultural expert said that biogas projects have become a major tool to help China achieve its energy-saving emission-reduction goals in rural areas.

China encouraged the development of biogas as part of the Renewable Energy Law, which became effective in 2008 year, and also as part of the country’s Mid- and Long-Term Development Program for Renewable Energy.

Cooking with biogas stove

22

THE BIOGAS ECONOMY ARRIVING

The biogas economy is taking off, but will it mean vast swathes of energy crops feeding enormous biogas plants instead of people, or distributed local generation for food and energy self-sufficiency while mitigating climate change

BIOGAS GERMANY FROM "ENERGY MAIZE"

Only a few years ago, the 'hydrogen economy' [1, 2] was on everyone's lips as the natural successor to our fossil fuel dominated carbon economy. Not anymore. A 'biogas economy' has emerged to take its place, at least for the foreseeable future.

In 2007 the German Greens commissioned a report on the potential of biogas in Europe from the Öko-Institut and the Institut für Energetik in Leipzig. The report, released to the media at the beginning of 2008, claims that Germany alone can produce more biogas by 2020 than all of the EU's current natural gas imports from Russia [3].

Biogas is booming in Germany and has become Europe's fastest growing renewable energy sector. The market leader Shmack Biogas has received €130 million in investments to expand its activities, and is involved in several large scale projects. One of these is to build Europe's biggest biogas plant with E.ON Ruhrgas and E.ON Bayern; it will be a 4 MW facility costing around €15.8 million [4]. After cleaning and upgrading, the high quality methane will be fed into the natural gas grid.

Another German biogas firm Agri.capital has secured €60 m in new equity funding [5]. The company owns and operates more than 35 biomass plants in Germany and Austria with combined capacity of more than 32 MW. The new equity investment will be used alongside a new €10 m debt facility to fund organic expansion across Europe and allow the firm to explore acquisitions. The company specialises in combined heat and power plants. It has also developed a number of biogas refineries that clean the resulting biogas to produce pure methane.

Biogas production in Germany relies to a large extent on dedicated energy crops such as maize, and has been a boon to the agricultural sector of the region around Schwandorf. For the first time, farmers there are growing "energy maize" crops guaranteed to be taken up by the biogas plant. Schmack Biogas's announcement in July 2007 made the unsubstantiated claim that energy maize "reduced the land needed to grow feedstock by up to a third" and can "restore degraded land and increase its fertility". It did not foresee the huge increases in food prices a year later due to the diversion of grains into producing energy [6], as a World Bank report confirmed [7] (see also Chapter 8).

Germany alone can produce more biogas by 2020 than all of the EU's current natural gas imports from Russia

Biogas is produced in the anaerobic digestion of organic wastes by communities of bacteria that occur naturally in livestock manure. It consists of 60 to 70 percent methane, which can be used as fuel like natural gas [8] (see Chapter 21). While it is true that biogas is produced much more efficiently from crops - a hectare of maize yields twice as much biogas energy than ethanol – its chief advantage is that it can be produced from a wide variety of organic wastes such as livestock manure, crop residues, food and food processing wastes, even paper and human manure, and in a distributed, decentralized way as so successfully demonstrated in China (Chapter 21). It also has the potential to decrease energy use by increasing energy efficiency in combined heat and power generation.

We have been promoting anaerobic digestion since 2005, for mitigating greenhouse gas (GHG) emissions and providing food and fuel security in the worsening 'peak oil' crisis [9-11]. So we are naturally pleased that the biogas economy is arriving.

The danger, however, is that the biogas economy will be hijacked by big companies for centralised power-generation from bio-energy crops, which may jeopardise our food security and prevent its full energy and carbon mitigating potentials and other benefits of distributed decentralised generation from being realised.

BIOGAS USA

A sure sign that the biogas economy will take off is that the United States is talking about it too. A new

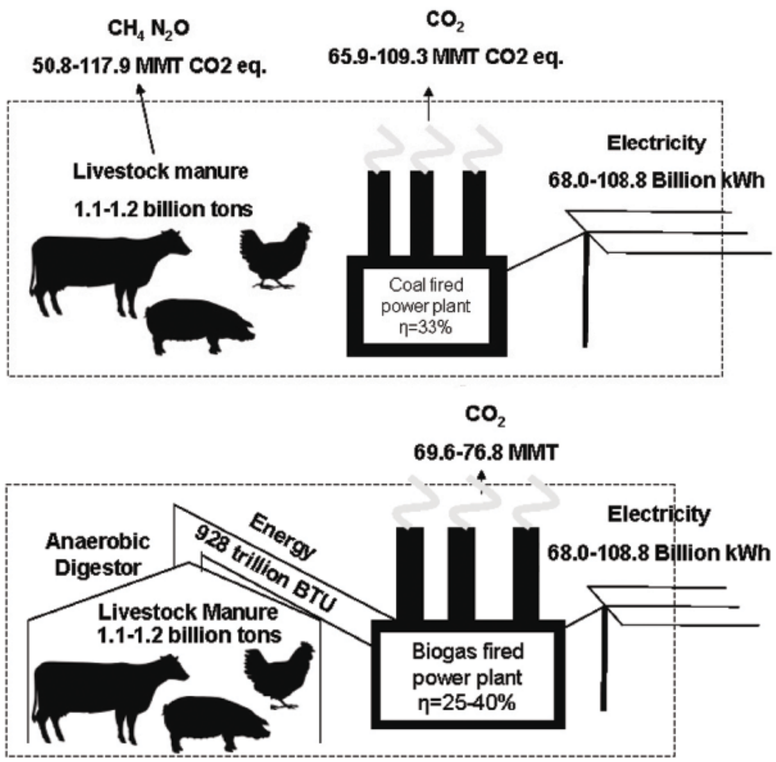

Figure 22.1 How anaerobic digestion of livestock manure saves energy and carbon emissions (see text)

study backs up the advantages of biogas from livestock manure.

The US livestock industry produces more than one billion tons of manure each year, most of it kept in lagoons or stored outdoors to decompose, polluting the land, water and air, and emitting an estimated 51 to 118 million metric tonnes of carbon dioxide equivalent (CO_2e) in methane and nitrous oxide, strong GHGs with global warming potentials of 21 and 310 respectively. (One metric tonne, or 1 000 kg, is equal to 1.102 US ton).

Chemical engineers Amanda Cuéllar and Michael Webber at the University of Texas, Austin, have taken a 'top down approach' and compared two scenarios for their combined energy and GHG emissions [12]. Scenario A is business as usual (Fig. 21.1, top panel), manure is left in a lagoon or in the open and coal is burnt to produce electricity. GHGs are emitted both from the manure and coal fire. Scenario B treats all the livestock manure in anaerobic digesters, which converts the wastes into biogas (Fig. 22.1, bottom panel). The resulting biogas is burned to generate electricity to offset coal-fired power, so the carbon dioxide from burning biogas is the only GHG emitted.

Summing up all the manure contributions from the different kinds of livestock, Cuéllar and Webbs found a total of 928 trillion British Thermal Unit (BTU) of energy available, which is about 1 percent of the country's energy use. And assuming biogas-fired power plants range in efficiency from 25 to 40 percent, between 68 and 108.8 TWh of electricity could be generated each year, about 1.8 to 2.9 percent of the country's electricity.

They then worked out the equivalent amount of coal that has to be burnt to generate the same amount of electricity at a typical efficiency of 33 percent for coal-fired plants, and compared the carbon dioxide emissions. Biogas from livestock manure represents a saving of between 47.2 and 150.4 Mt of CO_2, about 1.9 to 6 percent of the country's GHG emissions.

The US researchers have understated the case for biogas in many ways. Notably, co-digestion of other organic wastes will at least double, if not triple, the volume of biogas available, and because biogas methane can be purified as a renewable fuel for mobile uses for cars as well as farm machinery [9-11], it can displace larger amounts of fossil fuels, thereby contributing even more to mitigating GHGs and saving energy.

BIOGAS SWEDEN

Sweden has led the world in biogas use for buses and other vehicles since 1996 [13]. Biogas methane has to be cleaned and upgraded for vehicles to avoid corrosion and mechanical wear, and to meet quality requirements. Cleaning involves removing particles, traces of water and hydrogen sulphide. Upgrading involves removing carbon dioxide that makes up 30 to 40 percent of biogas. Cleaning and upgrading are done to a standard set in Sweden in 1999.

The most common method of upgrading is scrubbing with water under high pressure, the second most common method is Pressure Swing Adsorption: CO_2 is adsorbed on activated carbon at high pressure and released when the pressure is reduced down to vacuum Other methods are adsorption with organic solvents such as polyethylene glycol or a proprietary amine.

During 2006, 54 percent of the gas delivered to vehicles was biogas. By June 2007, there were 12 000 vehicles driving on upgraded biogas/ natural gas and the forecast predicts 500 filling stations and 70 000 vehicles by 2010 [14].
The sale of biogas for vehicles is increasing every year; it went up by 48 percent between 2005 and 2006, and by the end of 2006, there were 95 filling stations for biogas/natural gas.

The use of biogas as vehicle fuel in Sweden was started in the 1990s by municipalities or companies owned by municipalities. They saw the biogas generated at sewage treatment plants as a resource and a locally produced renewable fuel. Municipalities still play an important role as the majority of gas in Sweden comes from sewage treatment plants or municipal waste handling companies. Private companies have now stepped in to sell vehicle fuel and building filling stations. Energy companies like E.On Gas and Gothenburg Energy have invested in upgrading plants and actively working for more renewable gas.

Strong government support is important, it includes 30 percent investment support, zero tax, reduced income tax for company car users, and no congestion fees in the capital city of Stockholm.

If biogas can be injected into the gas grid (originally built to transport natural gas) then all of the gas from the biogas plants can be used. This would especially benefit medium to small scale biogas digesters sited on farms. Rather like the electricity grid for distributed generation from solar panels [15] (see Chapter 13), the gas grid also works as a backup and biogas can reach new customers. In Sweden, there is only natural gas in the western part of the country and so far, four biogas plants inject biogas into the grid.

In June 2009, a new bio-methane plant was announced in Stockholm by Swedish Biogas International [16]. The new plant, located in Skarpnäck, will supply the capital of Sweden with bio-methane both as vehicle fuel for buses and cars and for the new city gas grid. It will be the largest bio-methane plant in Sweden so far, with a production capacity of 10.5 million m^3 bio-methane a year; that will double production capacity in Stockholm, the volume corresponding to 31 percent of the whole Swedish market in 2008.

In fact, many countries that have not yet gone into anaerobic digestion to produce biogas are predisposed to take advantage of biogas. In Italy, for example, cars running on natural gas or on both natural gas and petrol are widespread. While on a study/lecture tour in Italy in July 2008, I was driven in a 17 year old 2 000 cc Audi that has been modified to run on either petrol or methane. By simply pushing a button next to the steering wheel, you can switch from one to the other smoothly while on the road. The modification, which cost €700, involved a tank for compressed methane in the boot, with a capacity of 11 m3, plus a 'lung', presumably a fuel-injection system for gas. Filling stations for methane are every 25 km on ordinary roads, though not on the motorway. The old Audi gave about 30 km per m^3 of methane containing about 40 MJ of energy, some 20 percent more than a litre of petrol. But methane appears to run the engine a bit more efficiently. Methane was selling at about €0.95 per m^3, and petrol at €1.50 or more a litre. For the same distance, it cost only 35 percent as much on methane as on petrol. No wonder people were all filling up on methane rather than diesel or petrol. Needless to say, as the price of petrol and diesel goes up, so does the price of natural gas; which is another reason to use biogas methane as fuel.

Germany and Austria also have cars already running on natural gas, and have both gone into biogas enthusiastically, though mostly using bio-energy crops as feedstock. They have set up national targets of 20 percent biogas in the gas sold to vehicles.

At the end of 2006, Germany had about 3 500 biogas plants with total electric capacity of 1.1 GW in operation [17]. Most of the new biogas plants have an electrical capacity between 400 – 800 kW. The first industrial biogas energy park, Klarsee, with 40 biogas plants (total capacity 20 MW, has come into operation. Energy crops are the main substrate, and manure constitutes less than 50 percent. Industrial companies built plants mainly for fermentation of energy crops. Germany is already growing energy crops on more than 1.3 million ha, or 11.4 percent of its arable land [18].

Currently, there are quite a few large biogas digesters at wastewater treatment plants, landfill gas installations, and industrial bio-waste processing facilities, and more are under construction (see above). But it has been predicted [17] that by 2020, the largest volume of produced biogas will come from farms and large co-digestion biogas plants, integrated into the farming and food-processing structures.

How much biogas energy can we realistically expect for Europe as a whole, counting both energy crops and livestock manure?

One estimate from the University of Southern Denmark [18] assumed that energy crops convert to biogas at an efficiency of 80 percent, as not all the compounds from biomass can be digested, for example lignin, and only around 25 percent of the energy crop will be dedicated for biogas production, the rest to be applied to other renewable energy production such as solid and liquid biofuels. The EU27 has a total land area of 433.2 Mha, of which 196.6 Mha is agricultural and 113.5 Mha arable. If 20 percent of arable land is dedicated to energy crops such as switch grass – so 5 percent goes to biogas - 45.5 Mtoe (megatonne of oil equivalent) of methane can be produced at a projected yield of 20 tonnes of solids/ha, about twice as high as currently achievable.

In addition, the EU27 produces 1 578 Mt of cow and pig manure a year. The animal production sector is responsible for 18 percent of the GHG emissions, which includes 37 percent of the anthropogenic methane and 65 percent of anthropogenic nitrous oxide. The total potential for methane from the livestock manure is 18.5 Mtoe.

Hence, a total of 64 Mtoe, or 71 200 million m^3 of methane can be produced by 2020 from energy crops grown on 5 percent of Europe's arable land, plus its mountains of livestock manure [18]. This does not quite make up for the 74 400 million m^3 of natural gas methane that EU currently imports from Russia [19].

Obviously, if all the energy crops on 20 percent of EU-27's arable land were to be converted into biogas methane – which makes sense as it is far more efficient than conversion into ethanol or biodiesel - the estimates improve by quite a lot, as it would yield 182 Mtoe, giving a total of 200.5 Mtoe, about 10 percent of the current EU energy consumption of about 2 Gtoe [20].

Natural gas consumption has increased in the last 30 years and now accounts for almost one quarter of the world's energy consumption. It is

Swedish International Biogas Plant in Orebro, Sweden projected to account for 43 percent by 2030. The theoretical potential of biogas methane in EU27 would produce enough to supply 15.5 percent of the natural gas consumption in Europe [19] (or considerably more if all energy crops were dedicated to biogas methane production). At the same time, the emissions of several toxic compounds like nitrogen oxides and reactive hydrocarbon can be reduced by up to 80 percent compared to petrol and diesel.

A big question mark is whether dedicating 20 percent of Europe's arable land to producing energy crops is sustainable in terms of food production and conservation of natural biodiversity. Practically all of the set-aside land would have to be pressed into crop production.

A big question mark is whether dedicating 20 percent of Europe's arable land to producing energy crops is sustainable in terms of food production and conservation of natural biodiversity. Practically all of the set-aside land would have to be pressed into crop production

ADVANTAGES OF SMALL SCALE LOCAL GENERATION

None of the estimates based on energy crops have taken into account the advantages of smaller scale local generation and consumption [9-11], which make energy crops unnecessary.

The total biogas generating capacity of the world in 2008 was estimated at 18.5 GW [21], with some 9 GW in China alone (see Chapter 21), where household micro-generation for heating and cooking predominates. Europe's contribution is 8.5 GW so far and set to grow.

Biogas methane produced and used locally gives substantial energy savings due to increased energy efficiency. The increase in efficiency could be as much as 70 percent. That is because the 'waste' heat produced in generating electricity can be retrieved for heating purposes, and local use of electricity avoids the losses due to long distance transport through power lines. When less than half of this is factored in, the energy and carbon mitigating potentials of biogas methane simply from organic wastes, without any energy crops, can be much greater, perhaps up to 50 percent or more in combination with organic agriculture and localised food systems [11].

Local small to micro-scale biogas generation is widely recognized as a boon to Third World countries [22]. As also demonstrated in rural China (Chapter 21), it is a key to improving living conditions and alleviating poverty; by providing self-sufficiency and energy autonomy to poor farmers. Anaerobic digestion has been developed as a classroom demonstration project by young African leader Obayomi Oatunbosun Adekeke in Nigeria [23], who is passionate to spread the biogas technology to eradicate poverty in Africa.

Our proposal for an integrated food and energy 'Dream Farm 2' built around anaerobic digestion to recycle wastes into resources for mitigating climate change and delivering food and energy self-sufficiency to local communities [10, 11] fits perfectly with the post-industrial decentralised local economies that renewable energies offer (see Chapter 11). Our proposal has been taken up enthusiastically all over the world. Two potential implementations are close to home, and offer an object lesson on the importance of respecting local cultural history and tradition when putting science and technology in place.

DREAM FARM 2 A WORK OF ART

The first is an old family farm of 80 ha partly owned by Henry Nicholls in West Sussex, a beautiful part of rural England [24]. The estate includes a two-storey Victorian farmhouse and 25 hectares of natural woodlands of beech, oak and white ash mixed with conifers, some perhaps 50 metres tall.

The fields are all under the UK government's 'higher level stewardship scheme', which involves keeping the meadows as permanent pastures in an organic regime to maximise natural biodiversity. Henry and his wife Susannah keep a herd of 42 cows and two bulls, traditional Herefords and pedigree Shorthorns bred for meat, completely grass fed and free to roam except for 5 months in winter when they are housed in an old unheated barn and fed on hay and silage, never grain. The total population of cattle is usually about 100 including the calves, which are fed by their own mother for a year, until she gives birth again, and the older calves are sold on to other farmers for 'fattening', leaving the mothers free to suckle their newborn calves. Every year 35 calves are sold.

In addition, 18 Portland Sheep - a rare breed - stay out in the field all the year round. Susannah has a passion for animals, and a name for her special pets.

Henry and Susannah run the entire farm themselves. They use 74 450 kWh energy in fossil fuels a year consisting of 26 301 kWh off farm use of white (ordinary) diesel for the car, and 4 500 litres of 'red diesel', or 48 150 kWh, for farm machinery. Red diesel is just diesel discounted for agricultural use, the cost of which has gone from £0.25 per litre in 2005 to £0.70 in 2007, nearly three-fold increase. In addition, they use 4 375 kWh electricity for cooking and lighting, and burn an unspecified amount of wood for heating. So the total energy use from non-renewable fossil fuels is 78 825 kWh a year.

How much energy can they get from anaerobic digestion of available wastes?

As the cattle are kept in the barn for only five months in the year, that's when their manure is available for the biogas digester. In the period, they generate a total of 700 tonnes of solid manure and bedding straw soaked with urine. Let's assume that half of the weight is solid manure, and the other half is straw. Solid manure is 20 percent solid matter whereas liquid manure is about 6 percent solid matter [25], so let's say 350 tonnes solid manure is equivalent to 1166.7 tonnes liquid manure. Liquid manure yields 25 m^3 biogas per tonne, whereas straw probably yields the same as grass; say about 100 m^3 per tonne. The total theoretical biogas yield is 64 167 m^3 biogas, or 38 500 m^3 of methane, which contains 427 737 kWh of energy, more than 5 times that the Nicholls consume in a year.

Combined heat and power generation at 30 percent efficiency for electricity would yield 128 321 kWh electricity, with 50 percent of the energy available, i.e., 213868.5 kWh for heating, some of which used in warming the biogas digester to about 40˚C for optimum production of methane. The large excess electricity could be sold to the National Grid.

Biogas methane also replaces firewood for heating, substituting for the wood biomass they now burn, which has been identified recently as a "major cause of harmful pollution" [26]. Wood smoke is the biggest contributor of many organic compounds including benzene, ethane and ethyne, all "known to be harmful to human health." Biogas, on the other hand, is a smokeless fuel, and when cleaned and upgraded, can be used as fuel to run farm machinery and mobile vehicles [3], as mentioned earlier. The farm would clearly benefit from installing a biogas digester, and an obvious site is next to the winter animal housing.

One main problem is that the biogas digester is used for only 5 months of the year and lying idle for the other 7 months. To accommodate the amount of waste over the 5 months will require a biogas digester approximately 150 m^3. One strategy is to use the spare capacity in the rest of the year (as a free community service or paid waste treatment service) for digesting food and crop wastes as well as slaughterhouse wastes. Obviously, that would increase the income stream from electricity exported to the grid.

The Nicholls' farm raised a very important aspect in implementation of Dream Farm 2. The abstract ideal of a Dream Farm 2 not only needs to adapt to local physical resources, but also give precedence to the cultural history and the strong feelings associated with the place and the people. They inspire us in the diverse ways that Dream Farm 2 can be implemented, as individual works or art that enhances and complements the utilitarian aims.

The particular farm and surrounding countryside are hauntingly beautiful historical monuments, a fitting tribute to the generations of farmers who love nature above all. There is such a reigning sense of peace and tranquillity that one is loathed to disturb a single blade of grass.

The Nicholls' farm raised a very important aspect in implementation of Dream Farm 2. The abstract ideal of a Dream Farm 2 not only needs to adapt to local physical resources, but also give precedence to the cultural history and the strong feelings associated with the place and the people

URBAN DREAM FARM 2 FOR LONDON?

A second potential implementation is possibly the first "Urban Dream Farm 2" in the world, the initiative of Alex Smith of Alara Organics in London, the capital city of the UK.

Alara's food factory is on an unusually green industrial estate just north of King Cross-St Pancras train stations and Camley Street Natural Park, a wildlife sanctuary on the banks of the Regents Canal. Further down Camley Street is St Pancras Old Church, the oldest Anglican parish church in London built on what was originally an

Henry Nicholls Farm collage by Julian Haffegee

Iron Age mound. The church stands in a beautiful cemetery garden re-designed by the author Thomas Hardy when he was a young architect and where the poet Percy Bysshe Shelley is reputed to have first met his wife Mary Shelley visiting the grave of her mother Mary Wollstonecraft. Johann Christian Bach, the son of the famous composer is also buried in St Pancras Gardens which form the grounds of the Hospital of Tropical Diseases and St Pancras Coroners Court.

Alex has already made a head start to the urban Dream Farm. Over the years, he has added to Alara's eclectic environment by planting a permaculture forest garden where lettuces, bee hives, and broad beans flourish along with a hundred fruit trees. The garden runs parallel with the railway tracks and is an urban green corridor stocked with blueberries, raspberries, elderberries, mulberries, passion fruit, pomegranate, kiwi, plums, pear and apple trees. Alex has also constructed a large pergola made of sweet chestnut and planted grapevines at each corner which will eventually entwine and climb with blackberries up the wooden framework. Beneath the pergola are stools and a table made of reclaimed marble where outdoor meetings can be held. A large metal cabin serving as Alex's garden shed is topped with a windmill to generate enough "live" electricity to read by.

The crucial next step is to install the first community scale biogas digester at Kings Cross. Alex has identified the various interested parties within his local community to target constant food waste streams for year round recycling. Alara's next door neighbour is Booker Cash & Carry, the country's largest food wholesalers with over 160 outlets. It is the land beside Booker's warehouse that the first community biogas digester will be set up. Currently it's a tangle of brambles and a mature apple tree, but it runs in a seamless continuation of the permaculture forest garden, and so would fit perfectly with the green development that Alex has begun.

Camden Council owns the land adjacent to Alara and Booker and has expressed an interest in the biogas project that could potentially recycle about 200 tonnes of kitchen waste borough-wide per year. This would include kitchen wastes from the local Elm Village housing estate as well as food wastes from Alara and Booker, the garden projects and other neighbouring food processors. In addition, Booker collects huge amounts of vegetable oil from their food networks that they want to recycle into bio-diesel.

Camden Council and Alex believe that a local community biogas project could provide a waste hub for around 120 social enterprise schemes that are part of the London Recycling Community Network (LCRN). A working model of an urban community biogas digester recycling scheme would provide multiple local benefits such as training and permanent employment to get people off the unemployment register and into green jobs. The education and employment side of the project would be co-ordinated by the SEED Foundation and planners from the Council have introduced Alex to the London Irish Centre, a local community group that will be participating in creating vegetable and herb gardens on the land in front of Alara and Booker.

Another direct benefit of the community biogas digester is the digestate, the solid, nutrient rich, compost-like material produced by anaerobic digestion (see Chapter 21). Alex is excited about the potential of digestate to transform the quality of the soil in his garden projects and in local parks and amenity spaces. He aims to put to put two tonnes of digestate onto the land around Alara every year. This will sequester more C in the soil and increase the carbon stock in the gardens and thus help mitigate climate change.

Alex plans to build a greenhouse over and around the biogas digester to heat it to a constant temperature of around 40 degrees centigrade. At this stage he wants to use materials that fit with the landscape and are sensitive to the zero waste criteria. He is hoping to build greenhouses from recycled car windscreens and may also use a converted car engine or generator to run off the biogas to heat the greenhouses. There is also scope for a combined heat and power system. The greenhouses would be suitable for growing tropical fruits such as bananas. Because this is a zero-carbon project the central focus of the anaerobic digestion system both in terms of raw materials going in and the energy coming out should be done without the use of any fossil fuels at all.

The ancient and historic lands around Kings Cross fascinate Alex. Queen Boudica is supposed to have lost her battle against the Romans here. The old name for Kings Cross is Battle Bridge, which crossed the River Fleet before 19th Century industrial development paved over it. The underground river runs past the old church which is the second oldest Christian church in the country; the first is in Glastonbury, near to where he was born. Alex is keen to develop the spiritual links to his local environment with sensitivity, boundless generosity and, I suspect, meditation. He also wants to enhance the practical links between local people to make the Urban Dream Farm 2 project more real and give it a sense of place. The planting of the first inner city vineyard in Alara's permaculture gardens growing rondo red grapes will be made into wine and consumed by the Kings Cross Terra Madre Group. "What can be done on a community level should be done," Alex says.

Kings Cross is one of largest brownfield sites in Western Europe, and highly accessible. Building UK's first community biogas digester here would set the standard for recycling food wastes into energy and crop fertilizer for a sustainable London and be an inspiration for the artists, writers, poets, scientists, musicians, environmentalists, architects, engineers, farmers, urban growers, everyone, for generations to come.

Alara collage by Sam Burcher


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23

THE COMMUNITY COOKER

An extraordinary recycling project turns rubbish into energy and potentially transforms slums into resource rich communities

community cooker in use

The disturbing scenes of human deprivation in the highly acclaimed movies Slum Dog Millionaire and The Constant Gardener [1] show the real-life slums in India and Africa overflowing with people and with refuse. But what if the piles of stinking rubbish could be converted into what urban slums need most of all: hot water for washing, pure water for drinking and heat for cooking?

Nairobi-born architect, Jim Archer has designed and implemented with the help of his Kenyan fellow Director Mumo Musuva and their Planning Systems Services team the 2008 World Architecture Festival (WAF) award-winning project in Kibera, Africa's largest slum, which does just that. The locals in the Laini Saba district in Kibera have been instrumental to the success of the project they call the "Jiko ya Jamii," that translates from Swahili into the "Community Cooker".

Agnes Aringo is a caterer at Jim's architectural firm in Nairobi. She works on the community cooker and reports that the cooker is versatile, and that it boils water, cooks vegetables, stews beef, bakes cakes, fries food, and can be used to prepare breakfast, lunch and dinner, and make cups of tea. The two ovens cook cakes very quickly and each is large enough to grill a whole goat. You can't tell that the fuel used to cook this food is the waste products from the slum. Agnes says, "Nothing is thrown away or should be thrown away in our environment" [2].

A COMMUNITY-LED COOKER

The slum dwellers themselves have solved several of the practical problems presented by the cooker project. Volunteers from various local youth groups collect, sort and store the garbage in metal racks adjacent to the cooker where it can dry. Materials that cannot be burnt such as rubber and glass are put to one side. Any other biodegradable scraps that fall through become compost manure [3].

The really useful solid waste materials like paper and plastic – bags, drinks bottles and packaging as well as food scraps from banana, cassava, maize cob and sugarcane peel, sawdust, and even the discarded carrier bags of human and animal excrement colloquially known as 'flying toilets' are forked up to the top level of the racks ready for incineration. All these items would normally be left to rot in the street, thrown into water courses, or dumped in local rivers.

At first, Jim was baffled as how to reward the sorters for their time and effort. "It's very simple," they said. "We will do the sorting for the public from say 6 am until midnight. But from midnight until 6am we will work the cooker for ourselves. We will make bread and we will bake buns and we will heat water. We will sell these and that's how we will make our money." From that moment on, Jim knew they had a working project.

Two taps are the only moving controls on the cooker, which has deliberately been kept very very simple to operate and to maintain. One tap controls a drip flow of recycled sump oil (dirty and discarded oil from vehicles) and one tap controls a drip flow of water. A drop of each falls in equal amounts onto a heated steel plate at the face of the firebox, where the water vaporises into hydrogen and oxygen, which causes a combustive reaction with the flames and increases the temperature. As the firebox gets hotter it heats the network of steel pipes that pass around the cooker. This resourceful technical innovation was the idea of a local man and self-taught furnace-builder Francis Gwehonah, who has helped double the firebox temperature from 300˚C to 600˚C.

HOW THE COMMUNITY COOKER COOKS

The cooker is made entirely of welded steel and has eight circular hotplates on the top. This is similar to a 'traditional' hob design except that the big metal cooking pots can be partially submerged into the hotplates to gain and retain heat from the firebox below. Hot food is served directly from the saucepans, or can be taken back home by the person who has collected rubbish, or purchased a token to exchange for cooking time. The cooker has two ovens under the hob, one either side of the firebox.

A tall and narrow chimney rises out of the firebox between the hotplates and reaches high above the slum. White vapour emerges like papal smoke wafting away the almost odourless fumes from the spotlessly clean kitchen area. Sliding down below the hob, a wide metal chute feeds a constant supply of rubbish from the storage racks into the firebox's hungry flames.

In theory, the community cooker should be operated 24 hours a day providing there are people to collect, sort and burn rubbish. A by-product of the incinerator-like cooking process is the relatively small amount of ash that collects beneath the firebox which it is hoped will undergo a second transformation into material to reduce fly menace in pit latrines and the smell from open sewers, once toxic levels of the ash have been tested and if found acceptable.

HOT WATER FOR WASHING

It costs Sh5 (5 Kenyan shillings, about US$ 0.06) to use the cooker to make a family meal. A local woman Elizabeth Mumbi reckons it's a bargain. She says, "I come here quite often, I find cooking at this communal place quite cost cutting. The Sh5 I pay to use the communal "jiko" is nothing. Imagine how little kerosene or charcoal this money can buy. Nothing costs this little any more [4]."

The cooker heats up water for washing which can be taken to a communal bathroom known as a "bafu". Four large water filled tanks are connected by pipes to each corner of the cooker roof. They act as a reservoir for up to 160 gallons of water at any one time. On average 50 people a day take hot water into the bafu closet, while as many as 200 people could wash from the rain water stored in the tanks.

Since the Laini Saba community cooker became operational in 2007, Jim Archer has drawn up plans to continue to improve the social and environmental conditions in Kibera still further [5]. He wants to increase the number of cookers significantly to one per every 50-70 households, which can contain as many as 20 members per household. Jim is planning to recycle waste water from bafu closets to flush through the open pit latrines that often block and overflow which are to be redesigned as "aqua privies". The runoff from the latrines or "aqua privies" can then be bio-digested and the resulting matter and moisture gravity fed to support the growth of vegetables, fruit trees and shrubs which would create green spaces within the slum.

In this system, waste from one activity is simply a precious resource for another. By recycling the flow of wastes in the environment, the levels of water consumption, ground pollution, fly and mosquito breeding grounds and disease are all reduced.

This resourceful technical innovation was the idea of a local man and self-taught furnace-builder Francis Gwehonah, who has helped double the firebox temperature from 300˚C to 600˚C

UNEP & BASCO PAINTS FUND PROJECT

TThe United Nations Environment Programme (UNEP) is a major supporter of the Community Cooker initiative and has stumped up $10 000 towards its installation. The project is part of the Nairobi River Basin Programme (NRBP) [6], designed to rehabilitate and restore the Nairobi rivers ecosystems to improve livelihoods and enhance biodiversity. UNEP and the Kenyan based Paint Manufacturers BASCO who have also generously contributed to the construction of the prototype are keen to fund more cookers around the slum. Jim's team has made the World Health Organizations (WHO) 800°C minimum temperature requirement for incinerators in the Developing World their benchmark for operational acceptability within the cooker's firebox.

Until the current temperature of 600˚C is increased a further 200˚C the rubbish will continue to pile up and the majority of people in Kibera at least will go without basic sanitation. However, Jim Archer is confident his team can raise the temperature, but until his patent pending design reaches 800°C, he reluctantly accepts that there should be no new community cookers.

COOKERS *NOT* CHARCOAL

According to the Nairobi Metropolitan Report 2030, 91 250 tonnes of charcoal biomass is used for energy every year in Kenya [7]. Contributing to this is several ‘temporary’ displaced persons camps, which permanently shelter well over 110 000 people in each. Women and children from these camps travel further and further every day to find wood and fuel for cooking. This activity continually denudes the countryside for miles around affecting both humans and animals who are both entirely dependent on the environment.

Recent research findings show that black carbon (BC), which is essentially the black soot resulting from the incomplete combustion of burning fossil fuels contribute to warming the planet fifty five percent as much as CO_2, and that reducing black carbon emissions may be the quickest, cheapest way to save the climate [8]. Community cookers will contribute a great deal to reducing BC emissions, and hence earn carbon credits if BC reduction is included in the Clean Development Mechanism of the Kyoto Protocol.

The German aid agency GTZ has expressed an interest in placing community cookers into the refugee camps they manage and Jim reckons that each camp would need a thousand cookers to sustain their populations. He believes that the money that could be earned through carbon credits from these cookers could be reinvested into a massive reforestation project of native trees undertaken by the refugees themselves.

An engineering company in the UK has offered to loan Jim the sensitive equipment he needs to establish much more precisely how much carbon is emitted from the community cooker and how that compares to the use of charcoal and kerosene plus the emissions from the piles of rubbish in Kibera. The Engineering practice ARUP and an NGO called JHPIEGO(who are an affiliate of John Hopkins University) the Kenyan Red Cross and the Centre for Sustainable Engineering in the UK, and the British based Charity Glad’s House are also actively interested in the slum cooker project.

LOW TECH IS THE FUTURE

There are seemingly infinite uses to which the basic concept of the community cooker can be applied for local development. These include kilns for clay bricks, pottery and tiles, small hot water systems for homes, hot food and water for hospitals, schools and colleges, hotels and lodges. However, Jim’s low tech and socially inclusive vision of change under challenging conditions may not appeal to everyone in an increasingly complicated and technologically driven world.

But what this relatively low cost and labour engaging project does do is to give people something that they have never had before, hot food and hot water on a regular basis. In addition, it demonstrates that local solutions to specific problems such as the global scourge of plastic and other waste can be transformed into the basic comforts necessary for human wellbeing.

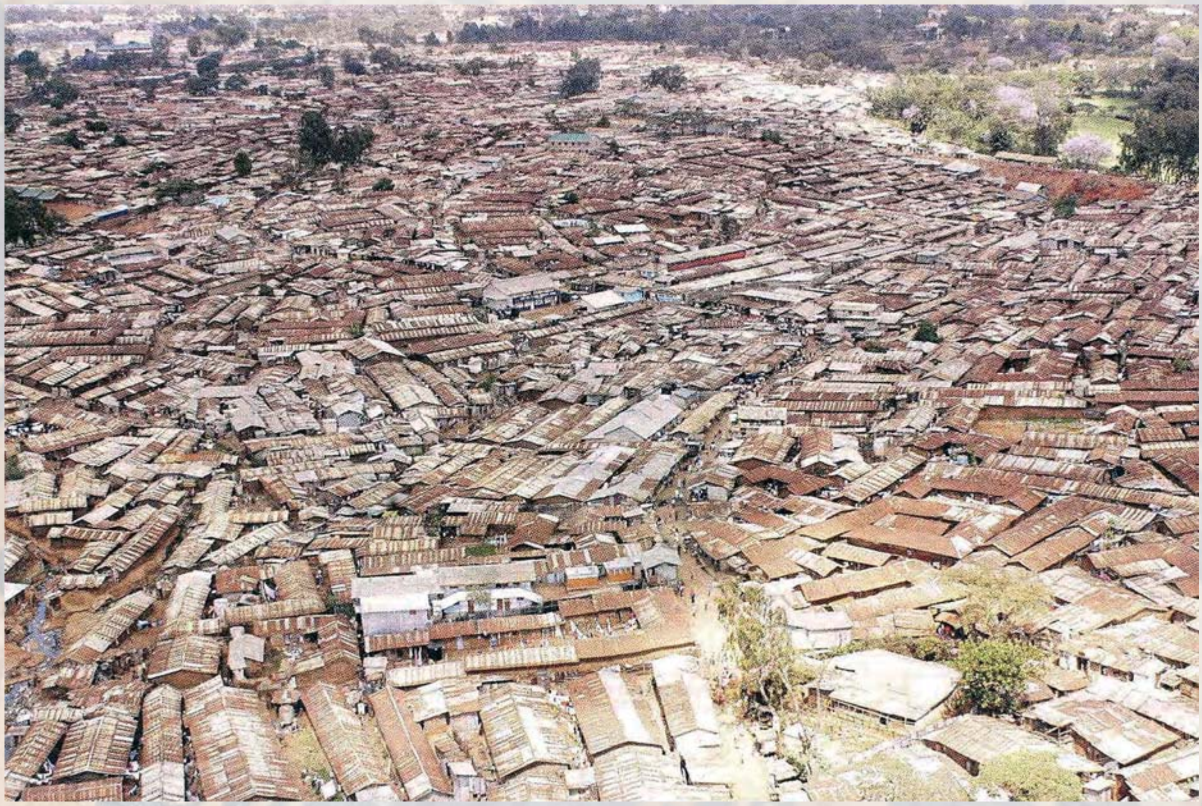
It is another example of the affordable, distributed, decentralised generation of renewable energy that gives local communities energy autonomy, which is a key to truly Green Energies.

CLEANING UP KIBERA

Kibera is a slum under the spotlight. This is because it is situated in the centre of a modern city and neighbours the United Nations Habitat Project – a UN agency for human settlement in Nairobi. Kibera has a colonial past and came about as a settlement for Nubian soldiers returning from active duty in World Wars I and II. Plots of land were given to the soldiers as a reward for their service. However, several factors make life very difficult to upgrade the impoverished living conditions in the slum. The principle problem is the refuse and rubbish that blocks up every piece of available ground makes laying of foundation for improving existing buildings very difficult. It is also chronically overpopulated with as many as 1.2 million people living there.

The land is Kibera officially belongs to the Government, but they have so far refused to officially recognise the settlement and therefore provide no basic services such as schools, clinics, running water or lavatories. The UN now intends to clear the slum over the next nine years at a cost of £1.2 billion as part of the Millennium Development Goals (MDG). They promise to relocate every single slum dweller in the city [9]. The Nubian community oppose this development.

Former Liberal Party leader and life time peer Lord David Steel is a fan of the community cooker and has seen it in action in Kibera. He says, “It’s a remarkable project that has lifted the standard of living for those people living at the very lowest levels. This is a model that should be reproduced and expanded widely to areas where it can really make a difference to people’s lives. It’s a fantastic idea that is inexpensive in comparison to other projects [10].”



Kibera as it is now

Kibera as it could be with planning

Architectural drawing and photograph of Kibera by James Archer, Planning Systems services Ltd.

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AIR CONDITIONING & ENERGY FROM DEEP WATERS

Deep lake and ocean water and even deep ground water is being exploited for cooling buildings, providing drinking water, and generating electricity

Thus spake the blue octopus

HOW CITIES & CAMPUSES KEEP COOL

Many great cities around the world are located near ocean shores or deep lakes. The cities of Toronto, Stockholm and Honolulu, and the Cornell University campus are showing the world what can be done using cold deep water to power the cooling of large buildings, providing a large saving in energy and cutting down on carbon emissions and pollution from energy generating plants.

The company Enwave District Energy Ltd initiated the cooling system in Toronto in 2004. A five-kilometre long pipe draws cold (4˚C) water from the depths (83 metres down) of Lake Ontario to Toronto Island (just off the Toronto shore) where the water is filtered and treated with chlorine as it is delivered to taps in homes and businesses. After treatment, part of the very cold water flows to a city plant that employs a heat exchanger (device that transfers heat from one liquid to another without allowing them to mix) to cool a closed water loop that circulates to the distribution network, where more heat exchangers cool the water circulating through the air conditioning systems in the office towers [1-3]. A total of 46 buildings were signed up to the system, including government buildings at Queen's Park. The system saves 85 GWh of energy and 79 000 tonnes CO_2 emission annually, the equivalent of 15 800 cars or a cooling load of 3.2 million m^2 [4].

Cornell University draws cold water from a nearby deep lake, Lake Cayuga. The water is pumped to a heat exchanger at the shore where the campus and a school share a cooling loop, and the warm water from the buildings flows down to push cool water up to the campus. The system is both elegant and cost effective [5].

Stockholm is using cold deep-sea water to cool buildings. In central Stockholm, the cooling plant comprises four heat pumps that obtain their energy from seawater. The plant has two seawater inlets, one at the surface and the other at a depth of 20 meters. Cooling is produced by cold water drawn through the inlet to a heat pump and then passes to heat exchangers that cool the water used to cool buildings in the central district. The heat exchangers are made of titanium to withstand the corrosive seawater. The surface inlet delivers water to the heat pump, which produces heating energy for delivery to the heating network [6].

Honolulu has been investigating alternative uses of seawater in cooling. The results were published as the proceedings of a 2003 workshop. One system draws very cool water from the offshore depths and delivers it to heat exchangers to cool hotels and other large buildings. The other system generates electrical energy using the stored energy of sun-warmed water to energize the evaporation of ammonia to drive turbines to create electricity (see OETC below) [7].

In 1986, the Natural Energy Laboratory of Hawaii Authority, Keahole Point, Hawaii began the successful utilization of seawater air-conditioning in their main laboratory building. Deep-water pipelines were already installed to provide cold, nutrient rich, seawater for research purposes in alternate energy and aquaculture. The cool water delivery pipes are set near the surface of the soil. This cools the soil and promotes fresh water condensation from the moist sea air. The cool air allows non-tropical food crops and flowers to grow in the cool moist soil irrigated by the condensed fresh water [8]. As a cold water supply was already incorporated into the infrastructure, they decided to use it for cooling. Today, seawater air-conditioning has been expanded to a new administration building and a second laboratory.

Installations for deep water cooling have been proposed for other locations in Hawaii including Kahoolawe, Kona Airport and the new town of Kapolei, Oahu [7]. Seawater cooling systems were under construction in Tahiti, Curacao, Korea, Malta, the Cape Verde Islands, Haiti and Mauritius [7, 9]. The Guam Power Authority put together an extensive report on the project at Tumon Bay [10]. However, this project has remained on the drawing board.

In 2009, the Guam and other projects in Hawaii, Puerto Rico, and the military base on Diego Garcia in the Indian Ocean were considered by Lockheed Martin and a few other companies [11]. The US Navy is interested in the technology and plans to explore it. Lockheed, together with another company, Makai Ocean Engineering, is pursuing the OETC technology described for Honolulu [7]. But the technology is expensive and can work in only a limited number of places, like the tropics, where there is a large difference in temperature between the ocean's layers. This excludes many major population centres. Also, it requires a lot of energy to pump the cold water through the system, and the potential ecological impacts of pumping a great deal of nutrient rich deep water from the depths cannot be ignored; even though natural upwelling of deep sea water delivers nutrients to the surface layers and contributes to the productivity of fisheries [12].

ENVIRONMENTAL IMPACT STUDY

A territory-wide system for cool water air-conditioning was planned for Hong Kong, the proposed project included consideration of environmental impact [13]. China undertook a study of the impact of proposed Chinese coastal municipal air conditioning using deep ocean water. The study dealt with the issue of warming deep water on the intensity of El Nino effects, and concluded that the impact of deep water-cooling to air-condition coastal cities was negligible at a coarse-grained level, but there could be local hotspots in temperature changes [14]. There has been no project so far.

ENERGY & WATER FROM DEEP OCEAN

The deep ocean has been put forward for the "blue revolution", a sink for converting the energy of sun-warmed surface water to electricity (ocean thermal energy conversion or OTEC) and at the same time enriching the surface waters with nutrients from the depths to support the growth of phytoplankton that sustains both fish and marine mammals [15]. Electricity can be generated from surface water warmed by the sun, while the cool water from the depths is used in the cooling cycles to drive turbines generating electricity.

The first OTEC was deployed in Hawaii in 1979 [16]. OETC systems include the closed-cycle system that uses a working fluid, such as ammonia, pumped around a closed loop with three components: a pump, a turbine and a heat exchanger (evaporator and condenser). The warm seawater passes through the evaporator and converts the ammonia liquid into high-pressure ammonia vapour. The high-pressure vapour is then fed into an expander where it drives a turbine connected to a generator. Low-pressure ammonia vapour leaving the turbine is passed through a condenser, where the cold seawater cools the ammonia, returning the ammonia back into a liquid. The open-cycle system is generally similar to the closed-cycle system and uses the same basic components. The open-cycle system uses the warm seawater as the working fluid. The warm seawater passing through the evaporator is converted to steam, which drives the turbine/generator. After leaving the turbine, the steam is cooled by the cold seawater to form desalinated water. The desalinated water is fresh water fit for domestic and commercial use.

The hybrid system uses parts of both open-cycle and closed-cycle systems to produce electricity and desalinated water. In this arrangement, electricity is generated in the closed-cycle system, and the warm and cold seawater discharges are passed through the flash evaporator and condenser of the open-cycle system (i.e., the original open-cycle system with the turbine/generator removed) to produce fresh water [17, 18].

Deep ocean water has also been used to provide fresh water from warm moist ocean air [19] or from warm surface water evaporated at low pressure then condensed using cool deep water [20]. With rapidly decreasing supplies of unpolluted fresh water, methods such as these can provide fresh water at relatively low cost without adding to global warming.

A UN report points to a potential threat to deep sea communities as food particles and organisms are sucked up with the cold water and hence removed from the deep water environment. Furthermore, the construction and maintenance of the pump and pipe systems could damage the surrounding habitat and its wildlife

In 1979, Japan began pumping deep ocean water to support fisheries whose productivity had been reduced by over-grazing. Upwelling of deep water replenishes surface water nutrients naturally, but productivity of offshore fisheries can be enhanced by pumping up deep water. Seaweed beds that support fish and marine mammals are frequently over-grazed and changed into barren sea. It has been possible to restore productivity by pumping up nutrient-rich deep water [21].

Pumping deep ocean water to air condition cities, produce energy and fresh water, and to fertilize the productive surface waters, appears a promising approach to mitigating global warming by reducing consumption of polluting oil and coal and the impact of overgrazing on marine food production.

Is the large scale pumping of deep ocean water sustainable? The deep ocean is ventilated through a giant thermohaline circulatory system that moves deep waters from north to south as salt-laden cooled water sinks into the depths in the North Atlantic and energizes a global conveyor belt that sends deep waters to the surface in the North Pacific, north Indian Ocean, and south-east Pacific [22]. This circulatory system is already being seriously disturbed by global warming [23].

A UN report [25, 26] points to a potential threat to deep sea communities as food particles and organisms are sucked up with the cold water and hence removed from the deep water environment. Furthermore, the construction and maintenance of the pump and pipe systems could damage the surrounding habitat and its wildlife.

These applications, if practised on a large enough scale, could contribute to warming the oceans, thereby decreasing its net primary production and impacting on all marine life [26].

SMALL SCALE AIR CONDITIONING

Similar technologies are definitely sustainable on a small scale, and there are increasing examples.

Even though London, England, is not located near a large source of cool water for air-conditioning, the underground railway has begun to use ground water to cool the tunnels for the comfort of the passengers. Groundwater seepage has been a growing problem causing damage to tracks and switches, so the seepage is simply bled off and used to cool the tunnels. The system promises to be both cost effective and cost-saving with regard to the maintenance of the railway [27].

For single-family homes, roof ponds seem to be the most desirable, though they must be installed with caution. The most effective system may be a roof pond upon which white cotton towels are floated on the surface using polystyrene strips; gunny bags also serve in place of towels. The towels resist heat transfer from the sun to the lower depths of the shallow pond [28]. The system is developed for tropical climates but might serve very well in areas with cold winters where the roof pond would accumulate insulating snow.

Deep flooded mines are also an excellent opportunity for air-conditioning. There are numerous spent mines in North America and Europe, and they have begun to be exploited for heating and cooling using geothermal heat pump systems [29]. There is a huge volume of deep-mine flood-water close to urban areas, or near land available for commercial development that can benefit from inexpensive heat and air conditioning. The cost of mine-water air conditioning is approximately half that of conventional air conditioning. Industrial coal mine water air conditioning facilities are operating in Springhill, Nova Scotia, Canada, and in Park Hill, Missouri in the United States, where a flooded lead mine is used to cool municipal buildings. Flooded coal mines in Shettleson, and Lumphinnans, Scotland, are used to heat and to cool numerous homes in the towns. Flooded mines are in the planning stages for heating and cooling in Timmins, Ontario in Canada; and in Poland, and Slovakia. The potential for developing geothermal cooling and heating is immense in North America and Europe and such constructions not only alleviate global warming but also provide jobs in a recession.

25

REEF FOR BARRAGE TO TAP THE TIDES

How to get tidal energy without damaging the environment

THE BARRAGE

The Severn estuary has long attracted the attention of engineers and various governments, who see the ebb and flow of its tides – reckoned to be third highest tidal range in the world - as a potential major contributor to the UK's use of renewable energy. By building a barrage across the estuary, engineers estimate that the 7 to 8 metre average tidal range could provide up to 5 per cent of the UK's electrical energy, with up to 8 gigawatts (GW) being generated at low tide when the water from the high tide has gathered behind the dam. The total primary energy consumption in the UK in 2007 was about 230 million tonnes of oil equivalent [1], with electricity consuming at least one third. On the basis of the barrage generating a 24 hour average of 2 GW, and, as 1 Mtoe is 11.630 GWh, it would yield 17 520 GWh/y, about 0.65 percent of UK's total primary energy and 2 per cent of total electricity [2]. That is under half the 5 per cent claimed by the Chartered Institution of Water and Environmental Management which has stated that the barrage would pay back its carbon footprint in construction in no more than 6 months [3].

Yet, since the Severn Barrage scheme estimated to cost £15 billion was first proposed many decades back, it has triggered widespread environmental concerns. A 2008 report [4], commissioned by the Royal Society for the Protection of Birds (RSPB), WWF-UK, the Anglers' Conservation Association, the National Trust, as well as fishery interests, such as the Wye Salmon Fishery Owners' Group, concluded that the costs of the barrage could not be justified on economic grounds, let alone the environmental devastation that its construction and operation would cause.

In its final form, and after a massive undertaking, the Severn Barrage would not only have to be big enough to extract the potential energy from the tidal head of 8 metres or more, it would also have to cope with powerful weather events, such as storm surges, and even sea level rise, now projected to be faster than estimated a few years ago. Electricity would be generated by a series of 40 megawatt underwater turbines during the two extremes of the tide. This would put a considerable strain on the central grid, which would have to cope with large surges in generation at times that while predictable, are not controllable.

As pointed out in the report [4], the barrage would inevitably lead to the loss of hundreds of square kilometres of mudflats and salt marsh, home to waders and other coastal birds as well as to a host of migratory species. Furthermore, on account of the delay in the natural tidal rhythm from penning in the water and then from the surge of water over each of the turbines when the gates are opened, its construction and use would alter drastically the currents in the estuary, playing havoc with the deposition of silt and having a profound impact on estuarine life, including fisheries and salmon runs.

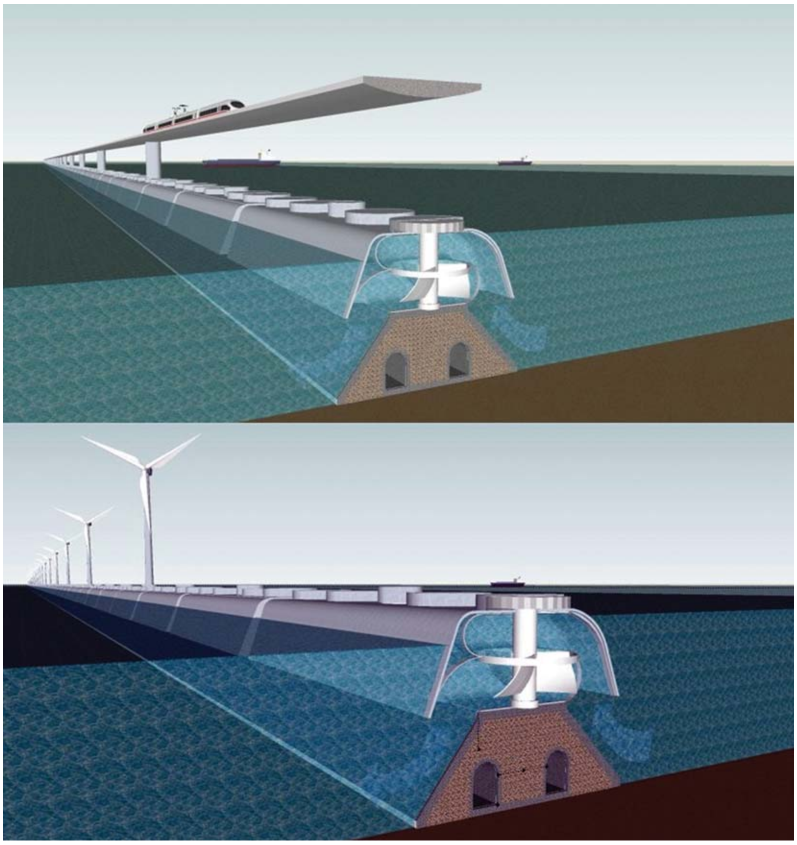


Figure 25.1 Cross section of the reef with caisson housing a turbine

THE REEF

Cornish hydraulics engineer Rupert Armstrong Evans believes the Cardiff-Weston Barrage across the Severn Estuary (as currently planned) is massively ill-conceived [5]. Instead, he has proposed a substantially different concept that he claims would generate as much electricity, but far more steadily than the big barrage, and would have a much reduced environmental impact. In particular, it would leave most of the mudflats and salt marsh intact.

Having pioneered electronic control systems that revolutionised the use of mini-hydro in the 1970s; and installed low-head hydraulic turbines which he designed for use in different parts of the world, from Cornwall, Wales, Scotland, to Nepal, India and South America, Rupert has come up with the innovative idea of a structure that has parallels with a tidal reef and so is designed to extract the energy from no more than two metres of tidal head.

In his tidal reef concept, Rupert proposed a semi-floating set of caissons (box-structures) to stretch across the estuary, thereby avoiding the massive high-head structure implied in the construction of the Severn Barrage. The fundamental difference between the barrage and reef is that, in the latter, the 1 000 turbines of some 10 metres in diameter would be housed within the floating caissons, themselves designed to ride over a fixed base structure on the estuary floor. By using a moveable 'crest gate' to track the tide level and therefore to maintain a small head difference, irrespective of the stage of the tide, the turbines would operate for long periods, and for at least double the generation period of the proposed big barrage. In addition, the reef would be far less vulnerable under adverse conditions than the barrage, on account of its smaller size and lower operating 'head'. In that respect, storm surges would easily go over the structure rather than battering it, as would be the case for the barrage (see Fig. 25.1).

Because the structure of the reef is more modest than the barrage, the saving on rock fill alone would amount to more than 10 million tonnes. At the same time, the passage of ships would be easier, as a single gate, similar in principal to the Thames Barrier, would allow the passage of even the largest ships with minimal disruption. This is only possible because of the small head difference across the structure. This system would also avoid the need to dredge a new deep-water shipping channel.

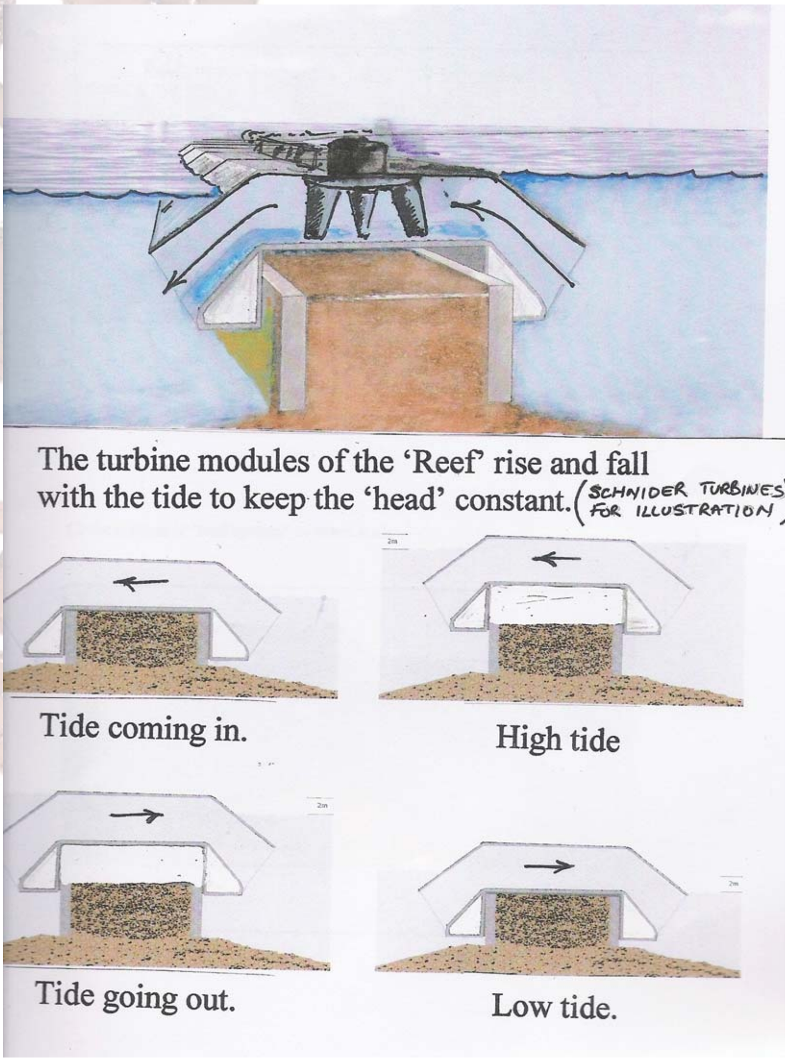
As Rupert points out, migratory fish should have no problems navigating the slow-moving turbines, and with the low head, any changes to the estuary flows will be significantly reduced, causing far less impact on the mud banks and salt marshes than would the barrage. Moreover, the time taken to construct the reef would be considerably less than for the barrage. Rupert refers to an excellent precedent in the construction of the Mulberry Harbour floating dock that was put together for the D-day Normandy landings. The various pieces of the dock were built in six months, before being successfully installed under enemy fire.

Rupert has had the backing of WS Atkins, the international engineering consultancy which, in 2008, declared that Rupert's Reef Scheme would not only generate more electricity but would cost considerably less – by some £2 billion - while simultaneously avoiding the worst environmental aspects of the Severn Barrage [6].

In the face of mounting concerns over the ecological damage that would result from constructing the barrage across the Severn estuary, Rupert's reef scheme has met with the approval of the RSPB. Furthermore, the government announced [7] it believes the 'Severn Tidal Power Reef' project to have merit, and was to commit financial support towards its future development.

In July 2009, however, a row broke out as Evan's idea entered in a Department of Energy and Climate Change Severn estuary competition, was rejected in favour of a fundamentally similar design put forward by Rolls-Royce and WS Atkins [8].

Migratory fish should have no problems navigating the slow-moving turbines, and with the low head, any changes to the estuary flows will be significantly reduced, causing far less impact on the mud banks and salt marshes than would the barrage



Reef wind and bridge artist impression

26

SALINE AGRICULTURE
TO FEED & FUEL THE WORLD

Shortage of fresh water is a greater threat to world food supply than shortage of fossil fuels; cultivating salt-tolerant crops could solve both problems

Sea farm by Mae-Wan Ho

People now use about half of the global supply of fresh water, and good fresh water is becoming an expensive resource. About 1 percent of the water on earth is fresh while another 1 percent is brackish (water that has more salt than fresh water, but not as much as seawater), while 98 percent is sea water. Agriculture not only has to compete for limited fresh water resources with home and industrial use; it is being threatened by the spread of soil salinization.

Irrigation of food and feed crops contributes to salinization. High rates of evaporation and transpiration lead to salt accumulation in the root zones as salts are drawn from the deep layers of the soil. Global warming also accelerates salinization as the sea level rises and floods coastal regions. Soil salinization is irreversible in arid regions because water is not available to leach the accumulated salts out of the soil. As salinity increases, crop yields decline, because most existing crop plants are not salt-tolerant.

SALINE AGRICULTURE TO THE RESCUE

To cope with the shortage of fresh water and increasing salinization of agricultural land, there has been renewed interest in saline agriculture: cultivating crops that are salt-tolerant, so they can grow in brackish water and sea water [1].

Two prominent advocates of saline agriculture are NASA scientists Robert Hendricks (Glenn Research Center, Cleveland, Ohio) and Dennis Bushnell (Langley Research Center, Hampton, Virginia). They want to see halophytes (salt-tolerant plants) being used for food, feed, and fuel [2].

They point out that halophytes could be grown in coastal areas, marshes, inland lakes, desert regions with subterranean brackish aquifers, and directly in oceans or seas. Cultivating halophytes would not compete for land that should be cultivating food [3]; it would provide more food and feed; and as added bonus, halophytes provide shoreline erosion protection and feeding areas for birds, fish and animals.

Some halophytes may even reclaim the land for freshwater plants. They can leach soil salt through enhanced percolation and, to some extent, through storing salt in their leaves that are harvested and removed from the fields.

By selecting and growing both micro and macro halophytes, we could get proteins, oils, and biomass to provide food, food, and fuel needs.

The oceans are also vast reservoirs of nutrients (nearly 80 percent of required plant nutrients) that could be recycled back to the land for greater sustainability in the grand circular eco-economy of nature [4].

Visions of large-scale industry based on halophytes go back to the 1990s [5, 6] when it was already seen to provide sustainable fuel-food supply while increasing the sequestration of carbon dioxide from the atmosphere.

S. bigelovii, farm2.static.flickr.com

K. virginica, farm2.static.flickr.com

Cultivating halophytes would not compete for land that should be cultivating food; it would provide more food and feed; and as added bonus, halophytes provide shoreline erosion protection and feeding areas for birds, fish and animals

HALOPHYTES FOR FOOD & FUEL

Bushnell [7] points out that there are some 10 000 halophytic plant species, of which 250 are potential staple crops. Vast land areas worldwide are salt affected and major regions overlay saline aquifers. A number of halophytes are now under development [2].The glasswort (*Salicornia bigelovli*) is a leafless annual salt-marsh plant with green jointed and succulent stems indigenous to the Arabian Sea coasts of Pakistan and India on the margin of salt lakes and Sri Lanka [8]. It produces seeds that are 30 percent oil and 35 percent protein; the oil is similar in fatty acid composition to safflower oil, and hence suitable for edible oil production. Its yield is also superior to soybeans and other oil seeds [2]. The seawater foundation has several hundred hectares under development.

The seashore mallow (*Kosteletzkya virginica*), a perennial, is one of the many salt-tolerant plants that grow wild on the coastal marshlands or inland brackish lakes, and serves as a source of both feed and fuel [9]. The oil content of the seed is 18 percent, similar to soybean with a fatty acid composition more like cotton seed; but unlike them both, it is a perennial, saving a lot of labour in resowing and sequestering more carbon in the deep roots (See [10] for the advantages of perennial crops which are being bred in the Land Institute, Kansas, in the USA to replace the annuals we now grow.)

Distichlis spicata, another perennial, is one of the halophyte grasses used in response to saline-affected lands, and is most suited to the high temperatures and high-radiation regimes in the summer months of southern Australia. In an extensive soil sampling survey conducted sites in Western Australia where *D. spicata* had been growing for 8 years, a marked improvement in the

D. spicata, farm2.static.flickr.com

Algae ponds, electricitybook.com

An area the size of the Sahara desert (13.6 percent of the world's arid and semi-arid area) would be sufficient to produce 16 times the energy used by the world in a year

soil was found compared to control soil, where no grass had been growing. There was a 12-fold increase in water percolation plus increases in carbon and nitrogen content [11]. Australia had an estimated 5.7 million hectares of saline-affected land in 2000, and projected to reach 17 million hectares by 2050. A test carried out there in 2002 [12] confirmed that several NyPa *Distichlis* cultivars grow well in sea water, with green matter yields up to 25 tonnes/ha and tolerating 1.5 times ocean salt conditions.

John Gallagher who heads the Halophyte Biotechnology Center at the University of Delaware has been developing halophytes cultivated in seawater for a long time [13], producing hay, protein rich grain, and a spinach-like vegetable.

ALGAE FOR BIODIESEL

There is a great deal of activity directed at producing biofuels from algae, the potential of which we reported earlier [14]. The hope is to find halophytic algae that produce more than 30 percent their biomass in oil, and cultivation methods that are commercially feasible [15]. Many companies have invested in research and development efforts to bring the cost of culture down and the production up to the goal of 50 g/m^2/day of dry biomass set by the US Department of Energy. Currently, an Israeli company Seambiotic maintains a 1 000 m^2 site that can produce approximately 23 g/m^2/day, according to its scientific advisor and algal growth expert Ami Ben-Amotz. This translates to more than 5 600 gallons/ha/year of algal oil, compared to palm oil yield at 1 187 gal/ha/y, Brazil ethanol at 1 604 gal/ha/y, and soy oil at 150 gal/ha/y.

Hendricks and Bushnell [9] estimate that the theoretical biomass conversion efficiency is 22 percent of the photosynthetic active radiation (400 to 700 nm), or 10 percent of total solar radiation, and is equivalent to 100 g dry biomass per day. In the case of algal oil, it would produce 24 500 gal/ha/y. As some 43 to 44 percent of the Earth landmass is arid or semi-arid, there is considerable potential for developing a multiplicity of seawater irrigated halophyte cultivation and algal aquaculture. An area the size of the Sahara desert (13.6 percent of the world's arid and semi-arid area) would be sufficient to produce 16 times the energy used by the world in a year (2004). On the current state of the art, algal aquaculture would produce 27.6 percent of the energy used in 2004.

LIVESTOCK THAT THRIVE ON HALOPHYTES

There is already research indicating that various livestock can thrive on halophytes or a combination of halophytes and conventional feed.

Sheep fed with halophyte forage were compared with sheep fed Bermuda grass forage or Bermuda grass mixed with salt to simulate the salt content of the halophyte. Halophyte-fed lambs gained weight at the same rate as control while the salt amended control gained significantly less. The halophyte diet appears to have contained balanced nutrients, which render their high salt level less detrimental than adding the same salt levels to Bermuda grass hay [16]. Cattle fed a halophytic grass gained weight equally to maize fodder fed controls [17]. An extensive review listed numerous halophytes including grasses and legumes that provide suitable forage for animals. The review indicated that grazing halophyte alone can result in salt overload for some animals so they stop feeding and begin to lose weight. A mixed ration of halophyte with conventional hay or maize is therefore advisable. The most salt tolerant farm animal is the camel, followed by sheep, then cattle, followed by horses, and the least tolerant are pigs and chickens [18]. Camels appear to be a promising source of meat in areas where halophytes irrigated with sea water can pasture large camel herds. Camels tolerate drinking water containing up to 2 percent sodium chloride while sea water contains in the range of 3.5 percent sodium chloride. Camels thrive while consuming brackish water and halophytes [19].

DOMESTICATING HALOPHYTES THE WAY AHEAD

As there are so many naturally salt-tolerant plants, researchers Jelte Rosema at the Free University, Amsterdam in the Netherlands, and Tim Flowers at the University of Sussex Brighton, in the UK think that the best way ahead is to domesticate wild plants and cross-breed them to produce higher yields [1, 20]. Plants such as sea kale and the asparagus-like samphire, which grow along the coast all over the world have been eaten for thousands of years. Sea kale is now farmed in the Netherlands. Spinach and beetroot are closely related to samphire, and crops such as sugar beet can grow well in salty conditions. .

Genetic modification experiments have been conducted for more than 30 years to try to make crops such as wheat or rice salt tolerant. But Rozema and Flowers say that the genetic manipulations necessary to achieve that for commercial growing may be too complex at present..

Rana Munns's research team at the Australian CSIRO (Commonwealth Scientific and Industrial Research Organisation) in Canberra have succeeded in breeding a new variety of salt-tolerant durum (pasta) wheat by crossing with an ancient Persian variety [21]. Modern durum wheat is not salt tolerant, but wheat originated from around the Mediterranean which is a heavily salt-affected area. So the researchers went back to the original wheat varieties to find some that were salt tolerant and crossed them into the current wheat. They knew that bread wheat tolerates salty soil, because its roots are good at excluding the salt and letting in the other nutrients, so they looked for salt in the leaves and selected for those that had hardly any salt in them. They found an ancient variety from what is today Iran, which they crossed with the modern durum wheat to get a new salt-tolerant variety. The ability to exclude sodium was associated with two genes *Nax1* and *Nax2* [22].

IDENTIFYING GENES IN SALT TOLERANCE

Substantial effort has been dedicated to identifying genes and genetic networks involved in salt tolerance, so that crop plants could be enhanced in salt tolerance by conventional selection and breeding. Another approach is to introduce transgenes into the crop plants to enhance salt tolerance, or influence expression of the salt tolerance genes. The naturally highly tolerant crops include beetroot, barley and rye. Moderately tolerant crops include spinach, rice, tomato, olive, wheat, cabbage and oats [23].

Identifying the genes for salt tolerance in halophytes facilitates the improvement of those crops but also provides a source of genes for improving the salt tolerance of conventional crops. Transcript profiling of salt tolerant red fescue grass (*Festuca rubra* ssp. Litoralis) revealed a complex regulatory network controlling salt stress response. The salt regulated transcripts included those involved in regulating gene transcription and signal transduction found in the cells of the root epidermis, cortex, endodermis and the vascular tissues; while other tissue cells had less active salt transcript activity. The gene transcription results showed coordinated control of ion homeostasis and water status at high salinity [24]. Heat stress was found to alter the expression of salt stress induced genes in the halophyte smooth cord grass [25].

Small proteins that regulate salt stress response in *Arabidopsis* were identified. Over-expressing one of those genes results in salt tolerance in the plant. Salt directly affects the small protein's signalling by inducing its degradation [26]. Proteomic analysis on grapevine revealed that 48 out of 800 proteins were altered after exposure to high salt, including 32 that were up regulated, 9 down regulated, and 2 newly expressed. The salt stress response suggests that salt spreads systematically throughout the plant [27]. A gene transcription map was used to identify a set of genes related to salt tolerance in salt-sensitive indica rice seedlings compared with a natural salt-tolerant relative. Over one thousand salt regulated genes were identified and several mapped to a QTL (quantitative locus) for salt-tolerance on chromosome 1. Selected members of the genes are considered candidate transgenes for crop improvement [28].

Small regulatory RNA response to salt stress was studied in maize roots. Micro array analysis identified 98 regulatory RNAs that were altered in activity following exposure to salt, along with 18 regulatory RNA molecules that were only active in salt tolerant maize [29].

The results of these studies do confirm the complexity of salt tolerance, which is why transgenesis has so far failed in produce salt tolerant crop plants beyond the greenhouse stage. On the other hand, these results will help considerably in enhancing the salt tolerance of crops by marker assisted conventional selective breeding.

NEW FRONTIERS

27

HARVESTING SUNLIGHT
WITH ARTIFICIAL PHOTOSYNTHESIS

Sunlight is by far the most abundant renewable zero-carbon energy resource, and artificial photosynthesis could be the most effective way to store the energy and make it more available and affordable

Solarium D1 by Mae-Wan Ho

Among renewable energies, by far the largest resource is provided by the sun [1]. Solar energy reaches the surface of the earth at the enormous rate of ~ 120 000 TW; but only a minute fraction, <0.0001 percent, is harnessed for use to produce the current global capacity of about 160 GW [2] (see Chapters 11 and 13).

STORAGE A MAJOR PROBLEM

There are numerous ways to harvest sunlight, which involves capture and conversion (see Chapter 15), but storing the energy is a problem.

The sun shines intermittently, and then only during the day. So it is necessary to have efficient and cost-effective storage capacity, if solar is to become a primary energy source for society. Solar power already leads in the renewable energies market, and as the world is shifting to renewable over conventional fossil energies, we should aim for an integration of capture, conversion, and storage functions for solar power.

Electricity, of course, can be stored in batteries, but batteries are still too costly. Another method is to store electrical energy mechanically by using it to pump water uphill; but this will mean charging and discharging on a 24 h diurnal cycle. For buffering the day/night cycle in the US energy demand, this would require the pumping capacity equivalent to more than 5 000 Hoover Dams filling and emptying reservoirs every day and night. In solar thermal, energy can be stored in water in an insulated thermal reservoir above or below ambient temperatures, which can then be used to heat spaces during the night or cool spaces during the day [3].

A method for storing solar energy has already been invented by nature – photosynthesis - which uses sunlight to split water, releasing oxygen while fixing carbon dioxide with the hydrogen, creating carbohydrates and biomass [4]. Photosynthesis has effectively provided the world with food, fibre, building material, and fuel (in biomass and fossil energies). The recent boom (and bust) of 'bioenergy' crops to supply 'biofuels' has been disastrous in accelerating deforestation and pushing up food prices especially in the developing world [5] (see Chapter 8). The potential of saline agriculture on brackish and salt-contaminated land, or in seawater (see previous chapter) in providing both additional food and fuel sustainably, on the other hand, has yet to be exploited.

The problem with photosynthesis, as far as capturing sunlight for other uses is concerned, is that it that it has not evolved to maximise efficiency in harvesting solar energy. Solar energy is rarely limiting; and plants have evolved many mechanisms to protect themselves from oxidative damages that strong sunlight can inflict.

It is estimated that the theoretical maximum efficiency of photosynthesis is ~9 percent [6]. This instantaneous efficiency would only be achievable under low light intensity, where every incident photon of appropriate wavelength can be absorbed and used for productive electron transfers (see below). Under full sunlight, natural photosynthesis uses only a fraction of the incident photons. Downstream carbon fixation further reduces the attainable efficiency; and many photosynthetic organisms have seasonal variations in photosynthetic rates. Consequently, on an annual basis, photosynthetic efficiencies average at best < 0.2 percent for land bioenergy crops and < 5 percent for microalgae [11] (but see [12] and previous chapter).

ARTIFICIAL PHOTOSYNTHESIS

One approach to storing solar energy is artificial photosynthesis, which attempts to replicate and improve on the natural process, mainly to obtain hydrogen as fuel for use in fuel cells that generate electricity by recombining the hydrogen with oxygen to form water.

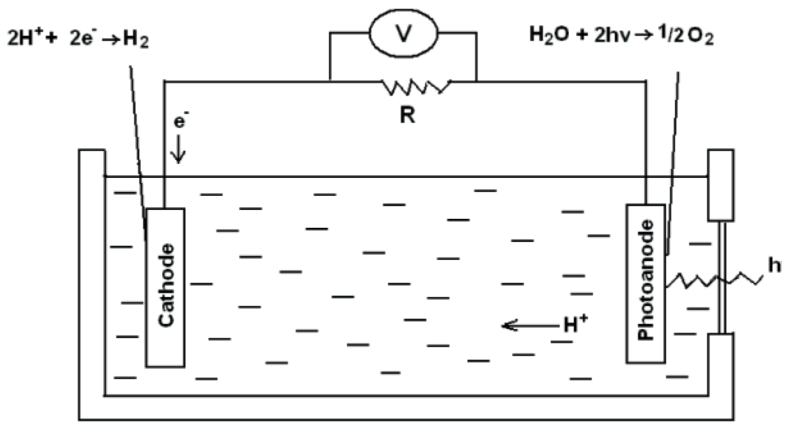


Figure 27.1 The photoelectrochemical cell

Photosynthesis has effectively provided the world with food, fibre, building material, and fuel (in biomass and fossil energies). The problem with photosynthesis, is that it that it has not evolved to maximise efficiency in harvesting solar energy

Artificial photosynthesis includes the photo-electrochemical (PEC) splitting of water into hydrogen and oxygen (the inverse of a fuel cell) (see Fig. 27.1) [13]. In a PEC system, a photoactive semiconductor material forms a junction in contact with a liquid or solid electrolyte. Because of the junction potential, electron-hole pairs are produced in the photoactive material on illumination. The light-induced electron-hole pairs (e^- and H^+ in the case of water) drive a chemical reduction (left, Fig. 27.1) and oxidation (right, Fig. 27.1)] leading to hydrogen and oxygen evolution respectively. Water is thereby split into its elements in two half-reactions, oxidation of water to oxygen, and reduction of protons to hydrogen, each of which requires its own catalyst and optimised conditions. In this way, the photon energy is converted directly into chemical energy rather than into electrical energy as with solid-state or electrochemical PV cells.

Artificial photosynthesis attempts to replicate and improve on the natural process, mainly to obtain hydrogen as fuel

CONVERTING SUNLIGHT INTO FUEL AND STORING ENERGY

The fundamental requirement for the conversion of sunlight into fuel is the oxidation of (removal of electrons from) a low energy electron source to produce a high energy reduced chemical species (that accepts electrons) [14]. In photosynthesis of green plants, water is the ultimate electron donor. Water is an ideal source of electrons because of its low energy content, abundance, and the production of O_2 which can be allowed to react on demand with the reduced fuel, H_2, for releasing energy.

The inter-conversion between oxygen and water is described by eq (1), where hν represents a photon of the appropriate wavelength for photosynthesis (see also Fig. 1).

Box 27.1
REDUCTION POTENTIAL
Reduction-oxidation reactions are the stuff of bioenergetics, and involve the transfer of electrons from one substance (donor) to another (acceptor) in accordance with their relative reduction potential. The reduction potential (also reduction-oxidation potential or redox potential) is the affinity of a substance for electrons. The value for each substance is compared to that of hydrogen, which is set arbitrarily to zero, at standard conditions of 25˚C, 1 atmosphere, and 1 M concentration.

Substances that have positive redox potentials accept electrons from hydrogen becoming reduced, while substances that have negative redox potentials donate electrons to hydrogen, becoming oxidized.

The redox potential is also the same as the electrochemical potential and the Fermi level used in solid state physics [15].

$$O_2 + 4h\nu \leftrightarrow 2H_2O \qquad (1)$$

In photosynthesis, the electrons extracted from water are boosted in energy by sunlight, so it can produce the high energy reduced chemical species. From a thermodynamic perspective, the production of hydrogen (reduced protons) is approximately equivalent to the reduction of coenzyme $NADP^+$ and ultimately, CO_2 to carbohydrates that takes place in green plants.

$$4H^+ + 4e^- \leftrightarrow 2H_2 \qquad (2)$$

Combination of the oxidative and reductive chemistry in photosynthesis gives eq. (3)

$$2H_2O \leftrightarrow 2H_2 + O_2 \qquad (3)$$

The change in energy can be estimated from the standard reduction potential $E^{0'}$ (also known as the reduction-oxidation (redox) potential, or electrochemical potential) (see Box 27.1)

$$\Delta E^{0'} = -1.23 \text{ V}$$

This is equivalent to a change in standard free energy (representing the energy stored in the fuel (H_2 or its equivalent in biomass) of

$$\Delta G^{0'} = 474 \text{ kJ mol}^{-1}$$

The subsequent reaction of this fuel with oxygen releases the stored solar energy in the reverse of equation (3), with $\Delta E0'$ of 1.23 V and $\Delta G0'$of -474 kJ mol^{-1}.

MAJOR ROADBLOCKS

The International Energy Agency, set up within the OECD (Organisation for Economic Co-operation and Development) during the 1974 oil crisis to address energy-related challenges in a collaborative manner, established its hydrogen programme (Hydrogen Implementing Agreement, HIA) in 1977. Included in the HIA is the photoelectrolytic production of hydrogen, which involved nine research groups from Japan, Sweden, Switzerland and the USA working together since 1999. A report published in 2004 said it has not achieved the ultimate goal of a stable sunlight-to-hydrogen conversion efficiency of 10 percent; but that goal was "in sight" [12].

The major roadblocks identified were as follows

- Lack of efficient light absorption material; for reasonable efficiencies, the semiconductor band gap must be less than about 2.2 eV but greater than about 1.6eV.
- Corrosion of the semiconductor; most semiconductors with appropriate band gaps are thermodynamically unstable in water, and
- Energetics of the semiconductor; matching the semiconductor band edge energies for the hydrogen and oxygen evolution reactions.

Some recent progress in overcoming these roadblocks will be described in the next chapters, which will also explain artificial photosynthesis in more detail.

28

MAKING FUEL FROM WATER

An efficient and robust catalyst for oxidizing water brings us closer to converting sunlight into fuel

Solarium d3 by Mae-Wan Ho

The holy grail of artificial photosynthesis is to mimic and improve on the green plant's ability to turn sunlight directly into electrochemical energy that can be used as fuel [1] (see previous chapter). Research and development in this area within the OECD (Organisation for Economic Co-operation and Development) countries date back to the 1970s; and major efforts have been renewed by the United States Department of Energy (DoE) since 2007 [2].

These efforts are paying off. Important progress has been made by researchers Heinz Frei and Feng Jiao at DoE's Lawrence Berkeley National Laboratory recently, bringing the dream of making fuel from water a bit closer to market. They've found that nano-sized crystals of cobalt oxide improves the status of the art 1 550-fold

"Effective photo-oxidation requires a catalyst that is both efficient in using solar photons and fast enough to keep up with the solar flux to avoid wasting those photons. Clusters of cobalt oxide nanocrystals are sufficiently efficient and fast, and also robust and abundant," said Frei [3]. "They perfectly fit the bill."

Inspired by nature's MnCa cluster of photosystem II; nature tends to use the most abundant materials, they focussed on Co_3O_4 nanoclusters, and struck gold

EFFICIENT & ROBUST CATALYST NEEDED

The direct conversion of carbon dioxide and water to fuel depends on the availability of efficient and robust catalysts for the photochemical transformations [4] (see next chapter). Catalysts need to have high turnover frequency (TOF) and density to keep up with the solar flux at ground level (1 000 Wm^{-2}) to avoid wasting incident solar photons. For example, a catalyst with a TOF of 100 s^{-1} requires a density of one catalytic site per square nanometre.

Catalysts with lower rates or taking up a larger space will require a high surface area nanostructure support that provides tens to hundreds of catalytic sites per square nanometre. Furthermore, catalysts need to work close to the thermodynamic potential of the redox reaction [1] so that a maximum fraction of the solar photon energy is converted to chemical energy. Stability considerations favour all-inorganic materials, as does the ability to withstand harsh reaction conditions of pH or temperature.

For the water oxidation half reaction, Jiang and Frei had found that iridium oxide fulfils these requirements in robustness, and has a reported TOF of 40 s^{-1} for IrO_2 colloidal particles suspended in water. The catalyst was driven by a $[Ru^{3+}(bpy)_3]$ unit (bpy, 2,2-bipyridine), generated photochemically with visible light using the established $[Ru^{2+}(bpy)_3]$/persulphate (electron donor/acceptor) system and a modest overpotential of 0.37V. (The overpotential is the potential in excess of the theoretical electrochemical potential of 1.23V required [1] due to inefficiencies in the system.)

The researchers earlier found that the all-inorganic IrO_2 nanoclusters (~ 2nm) directly coupled to a single centre chromium(VI) or a binuclear $TiCr^{III}$ charge-transfer chromophore (a chemical group that gives colour to the molecule) [4] evolved oxygen under visible light with good quantum yield. While iridium oxide closely approaches the efficiency and stability required as catalyst for oxidizing water, iridium is the least abundant metal on earth and therefore not suitable for use on a very large scale. So Jiao and Frei explored more abundant metals, inspired by nature's MnCa cluster of photosystem II; nature tends to use the most abundant materials [5]. They focussed on Co_3O_4 nanoclusters, and struck gold [6].

NANO-STRUCTURE COBALT OXIDE DOES IT

To form the Co_3O_4 nanoclusters, they used mesoporous silica (SBA-15) as the scaffold. The mesocopic structure of the silica consists of hollow channels connected by micropores. The Co_3O_4 clusters are formed exclusively inside the channels as parallel bundles of nanorods linked by short bridges, formed by Co_3O_4 growth in the micropores interconnecting the mesoscale channels. They loaded the silica at 4.2 and 8.6 percent by weight of Co_3O_4 in wet impregnation.

Transmission electron microscope images showed that the average spheroid-shaped bundle of Co_3O_4 has a short diameter of 35 nm and a long diameter of 65 nm for the sample prepared with 4.2 percent Co_3O_4; for the 8.6 percent sample, the short and long diameters were 65 and 170nm respectively. X-ray crystallographic analysis showed that the 4.2 percent samples were poorly crystallized, while the 8.6 percent sample corresponds to a 7.6 nm diameter rod structure. The 4.2 percent sample gave the highest rate of oxygen evolution when tested at pH 5.8 and 22˚C (with an overpotential of 0.35V), about 40 percent higher than the 8.6 percent sample. The rate was linear for the first 30 minutes before gradually levelling off. When fresh $Na_2S_2O_8$ electron acceptor was added and the pH value readjusted, oxygen evolution resumed at the initial rate. This finding confirmed that the slowdown was principally due to the consumption of the persulfate acceptor, and demonstrated that the activity of the CO_3O_4 nanoclusters did not degrade during photocatalysis in the several hours investigated.

In comparison, NiO nanocrystals in silica or micron sized Co_3O_4 particles were not effective. An estimated TOF of 1 140 s-1 per Co_3O_4 cluster was obtained in the 4.2 percent sample. The calculation is based on the geometry of the bundles of Co_3O_4 nanorods, bundle diameter 35 nm, rod diameter 7.6 nm, typically 14 rods per bundle, average rod length 50 nm. For the larger Co_3O_4 clusters (8.6 percent) the estimated TOF is 3 450 s-1. The calculation assumed Co_3O_4 nanorod spheroid bundles of 48 per bundle, rod diameter 7.6 nm, average rod length 130 nm. The oxygen yield was 65 times smaller for the aqueous suspension of 200 mg of bare Co_3O_4 particles compared with the 4.2 percent nanocrystals impregnated in silica. When normalised to the same amount of Co_3O_4 the O_2 yield for the silica impregnated nanocrystals at 4.2 percent exceeds that of the bare micron-sized particles by a factor of 1 550.

This was the first observation of efficient water oxidation, which is only half the artificial photosynthesis reaction. Nevertheless, the abundance of the metal oxide, the stability of the nanoclusters under use, the modest overpotential required, and the mild pH and temperature conditions make it a promising catalytic component for developing a viable integrated system for converting sunlight to fuel.

29

SPLITTING WATER WITH EASE

A specially designed metal complex splits water into hydrogen and oxygen and regenerates itself

Solarium d2 by Mae-Wan Ho

Splitting water is one of the ways to harvest sustainable energy from the sun, especially in creating hydrogen which can burn as clean fuel [1] (see Chapter 27). This imitates the natural process of photosynthesis in green plants that use sunlight to abstract hydrogen from water (to fix carbon dioxide into carbohydrates and ultimately biomass), liberating oxygen. Despite a great deal of effort, nothing practical has emerged so far.

David Milstein and his research group at the Weizmann Institute's Organic Chemistry Department in Israel have now found a new way of splitting water [2]. This involves the liberation of hydrogen *and* oxygen in consecutive heat and light driven steps, catalyzed by a single organic metal complex of the element ruthenium that the team has designed, in which the metal centre and the organic part attached to it cooperate in splitting the water molecules much more easily, it seems.

ORGANIC RUTHENIUM COMPLEX DOES IT

The team found that on mixing the ruthenium complex with water, the bonds between the hydrogen and oxygen in water break, with one hydrogen atom ending up binding to the organic part, while the hydroxyl group (OH) binds to the metal centre. When the water is heated to 100˚C, hydrogen gas is released from the complex, and another OH group attaches to the metal centre.

The most interesting part is the third light stage, says Milstein. "When we exposed this third complex to light at room temperature, not only was oxygen gas produced, but the metal complex also reverted back to its original state, which could be recycled for use in further reactions."

Most remarkable is the generation of a bond between two oxygen atoms (of the two OH groups) promoted by the metal complex, and it has been

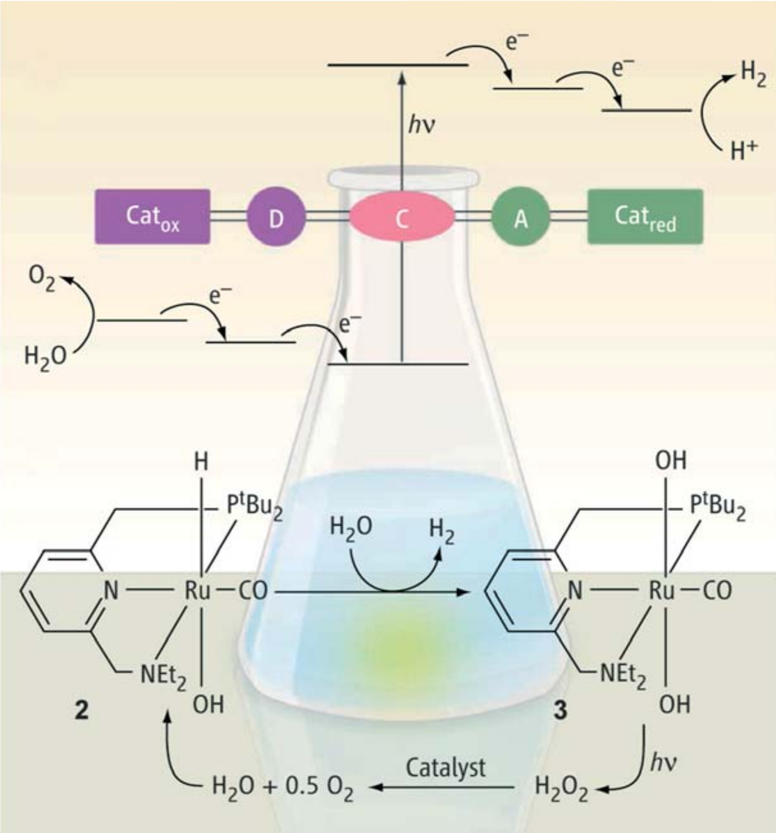


Figure 29.1 Comparison of photosynthesis-based water splitting with that of Milstein and coworkers (redrawn from [3])

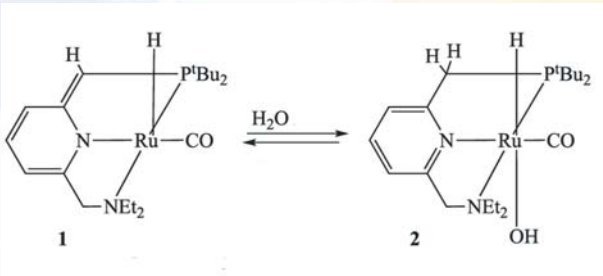


Figure 29.2 Ruthenium complex 1 is protonated by H_2O to complex 2, in which the OH group is coordinated to the ruthenium centre

The team found that on mixing the ruthenium complex with water, the bonds between the hydrogen and oxygen in water break. When the water is heated to 100˚C, hydrogen gas is released from the complex, and another OH group attaches to the metal centre. The most interesting is the third stage. When the resulting complex is exposed to light at room temperature, oxygen gas is released

unclear how it could take place. But Milstein and his team have worked out the new mechanism. Using a combination of heavy isotopes especially of H and O in water, they were able to track the actually molecular reactions involved [3]. These experiments showed that during the third stage, light provides the energy required to cause the two OH groups to get together to form hydrogen peroxide (H_2O_2), which then quickly breaks up into oxygen and water. The team provided evidence that the bond between the two oxygen atoms required in forming H_2O_2 is generated *within* a single molecule; that is, from a the two OH groups attached to a single metal centre, and not between oxygen atoms residing on separate molecules from different metal centres.

DEPARTS FROM PHOTOSYNTHESIS MODEL

A simplified version of the usual photosynthesis-based water splitting scheme (Figure 29.1, upper half) involves the absorption of a photon (hν) by the light-sensitive pigment, or chromophore (C), exciting an electron (e-) from its ground state to initiate the process of charge separation and charge transfer. The excited electron travels to an electron acceptor (A), leaving behind a positive hole that is filled by the electron donor (D). Proton reduction and hydrogen evolution occurs at the catalyst Cat_{red}, which accepts electrons, and water oxidation and oxygen evolution occurs at the other Cat_{ox}, which accepts holes [4]. Because the electrons and holes separate, water splitting is really two half reactions that either consume or generate electrons. Each half-reaction can be investigated and optimized independently, and research successes have been reported for both. But inevitably, a 'sacrificial' electron donor or acceptor is consumed in the reaction that is not optimised. Although H_2 has been generated by light induced chemical reactions, the efficiency and durability of the systems are still far from practical. The formation of O_2 is even more difficult (but see [5] previous chapter).

The organic ruthenium complex designed by Milstein's group works differently altogether. It depends on the reversible addition and subtraction of a proton (H^+) to an arm of the 'pincer' ligand holding the ruthenium ion. This usually difficult process is made possible through aromatization and dearomatization of the central ring of the pincer ligand. (This refers to the six-member ring in the aromatic form with three alternating double bonds inter-converting with one that has only two double bonds.) In the presence of water, protonation of the ligand arm, and binding of OH to the Ru metal centre takes place (see Fig. 29.2). The added proton becomes a captive source of H^+ that can react with the ruthenium bound hydride (H^-) to give H_2 gas, which is also an unusual reaction.

$$H^+ + H^- \rightarrow H_2 \qquad (1)$$

Ru complex 2, with hydride and hydroxide ions bound (RuH(OH)) can react with another H_2O molecule (see lower half of Fig.29.1). This reaction proceeds on heating to liberate H2 (as in reaction (1) above) and subsequent addition of water to form the dihydroxide complex 3 ($Ru(OH)_2$.

On exposure to light, $Ru(OH)_2$ eliminates the hydrogen peroxide. Rapid reaction of $2H_2O_2$ into O_2 and $2H_2O$ follows, completing the process of splitting water. This reaction also regenerates the ruthenium complex 1 which reacts with water to give complex 2, and so on to start another cycle.

The water-splitting scheme of Milstein and his team still has some way to go before it can be practical. "The project is directed, in the long run, for efficiently producing hydrogen from water using visible light, and without using sacrificial chemicals." David Milstein said. But the fact that a relatively simple molecular system can split water with mechanisms not previously conceived has excited the water-splitting community.

30

HARVESTING WASTE HEAT

Thermoelectric devices that scavenge waste heat to generate electricity improve efficiency of fuel consumption and replace greenhouse gas refrigerant

Going places by Jade Ho, USA

Automaker BMW is pushing ahead with its second-generation efficient Dynamics green car technology by harvesting waste heat from the exhaust and turning it into electricity [1]. BMW's head of development Klaus Draeger says it will boost fuel economy by some 5 percent on the combined cycle, and is expected to hit the showrooms by 2014.

The secret is a thermoelectric generator (TEG) similar to those that power satellites. By using waste heat from the engine's exhaust, around 200 W power could be generated.

In 2008, another automaker GM had already announced a thermoelectric car prototype in 2009 [2]. GM researcher Jihui Yang said that the TEG harvesting the exhaust heat will produce 800 W of electricity when its Suburban is cruising at about 50 to 60 miles per hour.

Box 30.1

THEMOELECTRIC EFFECT & ITS APPLICATIONS [5-9]

The thermoelectric (TE) effect converts temperature difference into electricity and *vice versa*. Historically it was the combination of three different observations.

Prussian physicist Thomas Johann Seebeck (1770-1831), discovered the *Seebeck* effect in 1821. A compass needle deflected when placed near a closed loop formed from two dissimilar metal conductors if the two junctions were kept at different temperatures. The magnitude of the deflection (indicative of a magnetic field) was proportional to the temperature difference and the type of conducting material, and not on the temperature distribution along the conductors. The *Seebeck coefficient* is defined as the open circuit voltage produced between two points on a conductor where a uniform temperature difference of 1 K exists between the two points.

The *Peltier effect* described in 1834 by French physicist Jean Charles Athanase Peltier (1785-1845) refers to thermal effects at the junctions of dissimilar conductors when an electric current is passed between the materials. Heat is absorbed or generated at the junctions depending on the direction of current flow.

The *Thomson effect* was predicted and subsequently experimentally observed by Willian Thomson, later Lord Kelvin (1824 – 1907) in 1851. It describes the heat generated or absorbed in a current-carrying conductor subjected to a temperature gradient. The three TE effects are related by the Kelvin relationship

Later in 1909 and 1911, German physicist Edmund Altenkirch showed that good thermoelectric materials should possess large Seebeck coefficients, high electrical conductivity (to minimise Joule heating due to electrical resistance) and low thermal conductivity (to retain heat at the junctions and maintain a large temperature gradient). These three properties were later embodied in the 'figure of merit', zT.

$$zT = T\,\frac{S^2\sigma}{\kappa} \qquad (1)$$

Where S is the Seebeck coefficient of the material (measured in microvolts/K), σ is its electrical conductivity, κ its thermal conductivity, and T the temperature in deg. K.

The development of semiconductors in the 1920s with Seebeck coefficients in excess of 100 microvolts/K increased interest in thermoelectricity. Russian physicist Abram Fedorovich Ioffe (1880-1960) showed in 1929 that a thermoelectric generator using semiconductors could achieve a conversion efficiency of 4 percent, with further possible improvement in its performance. By the 1950s, Ioffe and colleagues had developed the theory of thermoelectric conversion.

TE devices have been in production since the late 1950s, beginning with military applications, such as sensors of infrared imaging systems for heat-seeking missiles and night-vision systems. The development of silicon germanium high-temperature power-generation materials led to the production of heat engines for space applications with no moving parts that could operate in the absence of sunlight. All power sources for US and former USSR deep-space probes have used TE heat engines to convert heat generated by nuclear fissile material to electricity.

TE devices are now in mass production for cooling, heating, and temperature control applications. Miniature TE modules keep laser diodes at constant temperature to stabilize operating wavelengths. Polymerase Chain Reaction systems use TE devices to thermally cycle microlitre quantities of enzymatic reactions through exact series of temperature cycles. Climate-control systems have been developed for rapid seat cooling in the summer and equally fast heating in the winter. Portable beverage and picnic coolers were early commercial applications. Personal temperature-control systems that provide cooling as well as heating for the office have come onto the market, as have TE-based cooling systems for computer boards. One main application is power for remote data communication systems for oil and gas pipelines, polar weather station power generators, and cathodic protection for oil drilling platforms. TE generators are chosen for these applications because of their proven reliability (often maintenance-free for 20 years), durability under extreme conditions, and very little if any degradation in performance over their operating life time.

John Fairbanks of the US Department of the Environment said TEGs should be on the verge of production in about three years. The US Department of Energy's 'FreedomCar' target is for both cars and trucks to improve overall fuel economy by 10 percent [3].

The US Department of Energy's 'FreedomCar' target is for both cars and trucks to improve overall fuel economy by 10 percent using thermoelectric devices

Harvesting heat is particularly fascinating because heat is normally the end of the line as far as energy transformation is concerned. Turning it back into useful energy effectively recycles the waste energy thereby increasing overall energy efficiency. (This brings it closer to the circular thermodynamics of living organisms and sustainable systems [4]).

Another application high up on the list is air cooling and refrigeration, in replacing the need for the most common refrigerant R-134a used in home and automobile air conditions [3] that has a greenhouse warming potential 1 430 times that of CO_2. It will be banned in new European cars by 2011; and the US DoE announced a US$13 million cost-shared programme to develop TE technology for cooling.

What makes both heat harvesting and cooling applications possible is the thermoelectric (TE) effect, the conversion of temperature differences into electricity and vice versa. A thermoelectric generator creates an electrical voltage when there is a temperature difference on each side. Conversely, when a voltage is applied, it creates a temperature difference. Hence the effect, which depends on special TE solid state semiconducting material, can be used to generate electricity, or as a heat pump to heat or cool objects and spaces (see Box 30.1 for further details).

Another application high up on the list is air cooling and refrigeration, in replacing the need for the most common refrigerant R-134a used in home and automobile air conditions that has a greenhouse warming potential 1 430 times that of CO_2. It will be banned in new European cars by 2011; and the US DoE announced a US$13 million cost-shared programme to develop TE technology for cooling

THERMOELECTRIC DEVICES

The simplest TE device consists of a TE couple, two dissimilar semiconductors, a p-type and n-type [5]. It is connected electrically in series and thermally in parallel. To get a thermoelectric generator (Fig. 30.1 left), heat is pumped into one side of the couple and rejected from the opposite side. An electric current is produced in proportion to the temperature gradient between the hot and cold junctions. Electric current is propagated by electrons in the n-type semiconductor and by holes travelling in the opposite direction in the p-type semiconductor.

If a voltage is applied to the TE couple across in the right direction (Fig. 30.1, right), electron/hole pairs are created near the p-n junction. Electrons will flow away from the junction in the n-type material, as will holes in the p-type material, absorbing heat in the process and cooling the junction. Electron and hole recombine at the opposite end, generating heat. Thus it will effectively pump heat from the cold to the hot junction. The cold junction will rapidly drop below ambient temperature provided heat is removed from the hot side. The temperature gradient will vary according to the magnitude of current applied.

IMPROVING THE EFFICIENCY OF TE DEVICES

TE devices are easy to construct and robust in operation. The main drawback is the low efficiency. The dimensionless 'figure of merit' zT expresses the efficiency of the semiconducting materials that make up the TE couple (see Box 1). In today's best commercial TE cooling/heating modules, zT is about 1.0 [9], which gives an efficiency onequarter that of a conventional air-conditioning system using gas/liquid two-phase fluids, where the heat rejection and cooling parts of the system can be widely separated, and large temperature differences do not lead to the high heat backflow that destroys the efficiency of TE systems. Ideal TE system efficiency increases nonlinearly with zT, so to double efficiency, zT has to increase to about 2.2, and to achieve fourfold increase to equal efficiency of today's two-phase refrigeration, the zT would have to increase to more than 9.2.

In 1993, the US government's Office of Naval Research and Defense Advanced Research Project asked researchers to propose improvements of zT for cooling and heating applications. This has resulted in major efforts dedicated to making new semiconducting materials and improvements in the design of the modules. Only three efforts have produced zT values in excess of 2 [9], and they are still in the laboratory.

In 2008, researchers have boosted the zT of bulk semiconducting material to 1.5, (see Box 30.2), which is beginning to make thermoelectric devices commercially viable, particularly at the small scale, and in combination with other design improvements (see below).

Apart from increasing material zT, it is possible to making significant design improvements for thermodynamic efficiency and to reduce parasitic losses. Some examples are given by Lon Bell [9] at BSST, a company based in Irwindale, California. Using a counter flow pattern, heat transported from one fluid to the other is modified by the TE engines. In the cooling/heating mode (Fig.30.3 top), the TE elements boost the heat quality so that one of the opposing fluid streams is heated and the other cooled. The efficiency can be about double that of a single module operating with all the elements at the same temperature. In the power-generation mode (Fig. 30.3 bottom), the efficiency gains about 30 percent compared with TE heat engines in which the incoming working fluid is combusted without being preheated by the waste side of the array. This design is yet another example of the circular thermodynamics of organisms I referred to earlier [4].

The cycles can be combined with higher zT

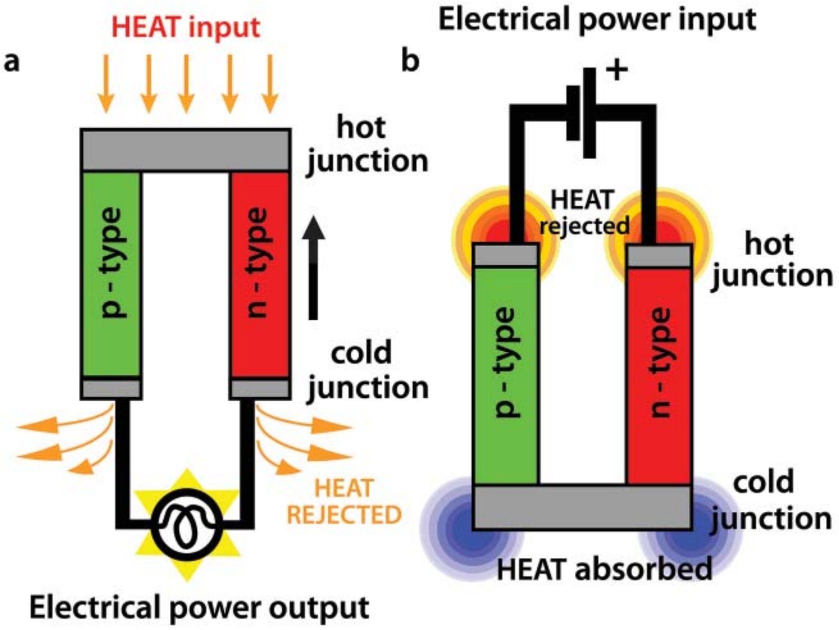


Figure 30.1 Thermoelectric device Left, generator; right, cooler

materials to compound the performance gains.

A further improvement is to reduce the amount of material used in construction. In real devices, system performance degrades as the device is made smaller, because the relative impact of parasitic electrical and thermal loss mechanisms increases as size decreases. Also, manufacturing tolerances and electrical isolation requirements place practical constraints on device size. An alternative, stacked configuration for TE elements,

Box 30.2
ENHANCING EFFICIENCY OF THERMOELECTRIC SEMICONDUCTORS

The efficiency of thermoelectric energy converters is limited by the figure of merit *zT* (see Box 30.1). One promising approach to increasing *zT* involves creating materials with nanometer-scaled morphology to dramatically lower the thermal conductivity κ by scattering phonons. Quantum-dot superlattices have reported values of *zT* > 2, and silicon nanowires have such a reduced κ that *zT* approached that of commercial materials. But these are still in the laboratory and not in bulk material that can be used commercially.

In 2008, two research teams reported significant improvements in zT of bulk semi-conducting material that are much closer to the market.

The research team led by US scientists Gang Chen at MIT Cambridge, and Zhifeng Ren at Boston College Chestnut Hill, in Massachusetts, significantly boosted *zT* simply by ball-milling crystalline ingots of p-type bismuth antimony telluride BixSb2-xTe3, and hot pressing the nanopowders into solid discs [10]. When tested, these solids gave a peak *zT* of 1.4 at 100˚C. The enhanced *zT* is the result of a significant reduction in thermal conductivity due to strong phonon scattering by interfaces in the nanostructures. Apart from the peak *zT* of 1.4 at 100˚C, the material has a *zT* of about 1.2 at room temperature and 0.8 at 250˚C. In comparison, conventional Bi2Te3-based materials commercially used have a peak *zT* of about 1 at room temperature and about 0.25 at 250˚C. The high *zT* of the present material in the 25˚C to 250˚C range makes attractive for cooling and for low-grade waste-heat recovery applications, such as (suggested elsewhere) harvesting body heat to run electrical devices [11]!

The research team led by Joseph Heremans at Ohio State University, Columbus, in the United States took another approach, working on the p-type material lead telluride PbTe. Its minimum thermal conductivity is already quite low, and they decided that progress must come from other sources, in the numerator of eq. (1), such as the Seebeck coefficient S.

The research team succeeded in doing just that, by doping PbTe with thallium [12]. At a level of doping of 2 percent thallium, *zT* was increased to 1.5 at 773˚K, and still increasing. It appears that thallium distorts the electron density of the material, increasing it over a narrow range, probably due to the valence band of the host semiconductor resonating with one energy level of a localized thallium atom in the semiconductor matrix. The temperature range where the TlPbTe material exhibits high zT values is particularly appealing for power generation from waste heat sources such as the automobile exhaust.

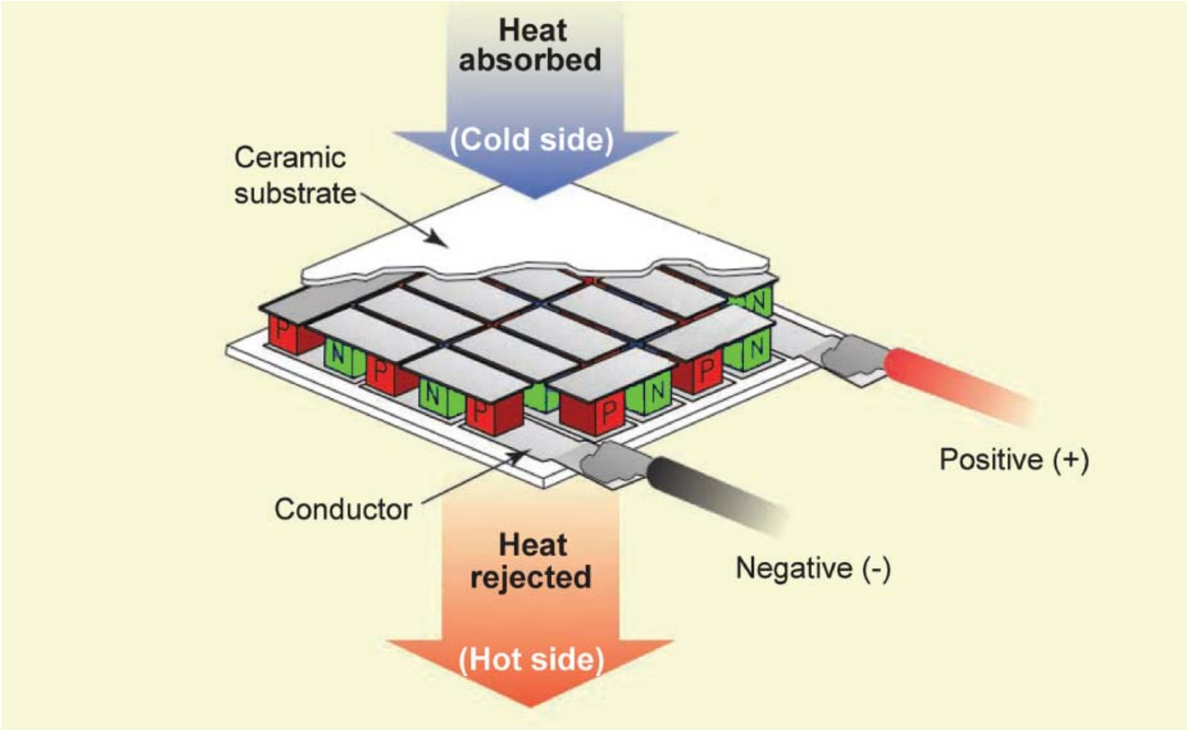


Figure 30.2 A thermoelectric module

Because of their ruggedness, portability, and ready ability to be electrically powered, TE systems should provide more-efficient and better performing temperature control in vehicles of many types including cars, trucks, trains and aircraft

for example, reduces parasitic losses from the electrical connections, and better still, if used in combination with a reduction in the electrical resistance at the TE material/shunt interfaces. Under many practical operating conditions, the weight of TE material used can be reduced by a factor of 6 to a factor of 25. The stacked configuration, for example, reduces material costs considerably for high-capacity system. For TE cooling and heating systems, the traditional configuration is cost-competitive up to about 400 thermal Watts output, but increases to about 4 000 W with the stacked design.

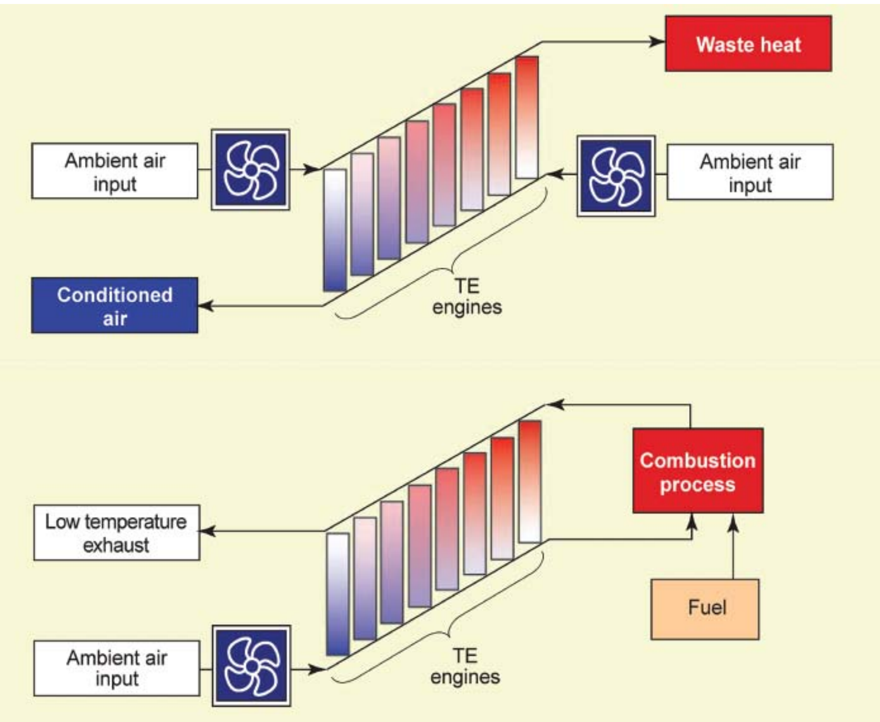


Figure 30.3 Thermodynamic cycles to optimize the performance of TE engines Top, cooling mode; bottom, power generation mode

TE FUTURE WITHIN REACH

Average zT in the range from 1.5 to 2 would enable substantial waste-heat harvesting as well as primary power-generation applications. Various government-sponsored programmes are underway in the US and Japan to increase vehicle fuel mileage by converting a fraction of the heat in the exhaust of trucks and cars to electric power (see above). The power would be available for power steering, brakes, water pumps, and turbo chargers could replace other vehicle subsystems such as the alternator, thereby reducing the weight carried. The energy target of 10 percent fuel reduction is within reach [9].

Gains of 5 to 10 percent would be possible in the small scale diesel-powered cogenerators that are becoming widely used in developed countries and for 5 000 to 20 000W primary generators in developing countries. In another proposed co-generator concept, the solar spectrum is split into shorter wavelengths that yield high photovoltaic conversion efficiency and longer wavelengths that heat a TE generator.

Another potential application, I suggest, is to use heat from low energy nuclear reactions (also referred to as condensed matter nuclear reactions) [13, 14] (see Chapter 31 and 34) to generate electricity with TEGs.

Industrial waste-heat recovery in aluminium smelting, glass manufacture, and cement production is practical at zT of 2. At the same zT, it may also be possible to replace small internal combustion engines such as those used in lawn mowers, blowers, and small outboard motorboats with external combustion TE engines, These engines would be very quiet and nearly vibration free. They would burn a wide spectrum of fuels, such as propane, butane, natural gas. Burning biogas methane with such external combustion TE engines [15] (see Chapter 22) would free us from fossil fuels.

If the average *zT* reaches 2, room, home, and commercial TE heating ventilating and air-cooling systems become practical, replacing R-134a.

Because of their ruggedness, portability, and ready ability to be electrically powered, TE systems should provide more-efficient and better performing temperature control in vehicles of many types including cars, trucks, trains and aircraft.

31

COLD FUSION

TO CONDENSED MATTER NUCLEAR SCIENCE

Cold fusion enthusiasts are pioneering a new discipline that has the potential to offer cheap, clean, safe nuclear energy, and more

Firing up by Li Poon

THE FUSION THAT CAME IN FROM THE COLD

Nuclear fusion, as conventionally understood, is a process whereby the nuclei of light elements fuse together to form heavier ones. (See Box 31.1 for a quick primer on atoms and nuclei.)

As conventionally understood, nuclear fusions only take place in our sun and other stars, and produce all the chemical elements starting from the lightest, hydrogen. The fusion of light elements releases enormous amounts of energy, whereas the synthesis of the heaviest elements absorbs so much energy that it only takes place in supernova explosions [1].

It requires a lot of energy to force even the lightest nuclei to fuse. That is because all nuclei are positively charged due to protons, and as like charges repel, nuclei strongly resist being too close together. However, should they get beyond this 'Coulomb barrier' a strong nuclear attractive force takes over and cause the nuclei to fuse. This is achieved by accelerating the nuclei to very high speeds by heating to 'thermonuclear' temperatures in excess of 10^6 °K. Only then can the nuclei get close enough by random collision to fuse together. Once the fusion starts, it generates so much excess heat that it becomes a sustained chain reaction. The hydrogen bomb is an uncontrolled fusion chain reaction.

The deuterium-tritium fusion reaction is currently considered the most promising for producing 'clean' nuclear energy. It produces helium and a neutron, together with 17.6 MeV (megaelectron volts) of energy.

$$^2H_1 + {}^3H_1 \rightarrow {}^4He_1 \text{ (3.5 MeV)} + n \text{ (14.1 MeV)} \quad (1)$$

However, there has been no success as yet in producing a workable design for a hot fusion reactor that is safe and controllable.

In 1989, Martin Fleishmann at the University of Southampton in the UK and Stanley Pons at the University of Utah Salt Lake City in the United States published a preliminary note claiming that atomic nuclei could be made to fuse at ordinary temperatures, with the release of considerable 'excess energy', i.e., energy in excess of input and much more than could be accounted for by ordinary chemical reactions [2].

A barrage of disbelief and derision greeted their publication, as it was tantamount to claiming that nuclear reactions similar to those that created the hydrogen bomb could be made to happen on an ordinary lab bench, with nothing more sophisticated than passing current through metal electrodes immersed in some salt solutions.

"Cold fusion" has had such a bad press over the past 18 years that I heard of one woman referring to having sex with her estranged husband in those terms.

But a small international community of scientists became impressed, especially when Fleischmann and Pons published more substantial results in 1990 [3], documenting the accuracy of their measurements and answering many of the criticisms made against their preliminary findings published the year before.

These cold fusion enthusiasts managed to keep the research going with small sporadic funding from their governments or private investors. They held well over a dozen international conferences, and in 2004 renamed their subject more appropriately, "Condensed Matter Nuclear Science" [4] in recognition of the important feature that atomic nuclei trapped in condensed matter can react at far lower temperatures than the usual thermonuclear reactions taking place by random collisions of highly energetic nuclei.

At the beginning of 2007, the Royal Society of Chemistry put "cold fusion back on the menu" in a report with that title [5]. There was an invited symposium focusing on cold fusion - also referred to as low energy nuclear reactions - at the American Chemical Society (ACS) 2007 Conference in Chicago. This was the first such symposium that anyone could remember. The programme chair of the ACS' division of environmental chemistry felt that with the world facing an energy crisis, it was worth exploring all possibilities.

More significantly, a lot of evidence has accumulated to vindicate Fleishmann and Pons' cold fusion claim, the latest coming from the US Space and Naval Warfare Systems Centre (SPAWAR) in San Diego California.

Fleishmann and Pons had packed deuterium into a palladium lattice by electrolysis of heavy water. The palladium electrode absorbed a lot of deuterium and the nuclei fused together, generating energy far in excess (about 1 000 fold) of any ordinary electrochemical reactions.

The SPAWAR researchers deposited palladium and deuterium together onto an electrode and speeded up the fusion process with an external electric field (parallel to the electrode surface). And using a plastic detector placed next to the electrode, the expected products of the nuclear reactions were identified [6].

The implications of cold fusion are enormous. It means that a cheap, much safer and controllable source of nuclear energy is on the horizon. Furthermore, it may be possible to use the same

ATOMS AND NUCLEI

An atom is the smallest unit of a chemical element. It consists of a core *nucleus* containing *protons* and *neutrons*, surrounded by electrons on the outside. Protons carry a positive charge, which is balanced by the negative charge of the electrons, so that the atom is electrically neutral as a whole. Neutrons do not carry any electric charge.

The elements are identified by their *atomic number Z* - the number of protons, the same as the number of electrons - and *atomic mass A* - the total number of protons and neutrons - the mass of electron is very much smaller and therefore neglected in the atomic mass. The simplest element is hydrogen; it consists of a single proton and a single electron, and is represented as $^1H_1$. Helium is the next simplest element with 2 protons and 2 neutrons, and is represented as $^4He_2$. Most elements exist as isotopes, different forms that have the same number of protons but different numbers of neutrons. Thus, hydrogen has two other isotopes, which unusually are given names of their own, deuterium and tritium, with one and two neutrons respectively, written as $^2H_1$ and $^3H_1$ (though they tend to be written often as D and T).

The protons and neutrons in the atomic nucleus are held together by *strong forces*, which overcome the electromagnetic repulsion between the positively charged protons. Strong forces act only at very close range; beyond that, *weak forces* due to electromagnetic interactions take over, so like charges repel and opposite charges attract.

kinds of low energy nuclear reactions to transform existing hazardous radioactive nuclear wastes into more stable, non-radioactive elements.

The implications of cold fusion are enormous. It means that a cheap, much safer and controllable source of nuclear energy is on the horizon

THE FLEISHMAN-PONS REACTION

The Fleishman-Pons reactor is a simple electrolytic cell enclosed in a Dewar flask (a sophisticated thermos flask, an insulated container having a double wall with a vacuum between the walls and silvered surfaces facing the vacuum. This enabled them to make accurate measurements of the rates of heat generation as light or heavy water is split by electrolysis [3]. Light water is ordinary H_2O, while heavy water is deuterium oxide, D_2O, deuterium being an isotope of hydrogen with the same atomic number and twice the atomic mass.

In the electrolytic cell, palladium (Pd) was the cathode and platinum the anode. The electrolyte solution contained lithium salts dissolved either in light or heavy water. When electric current is passed through the electrolyte, the water splits into hydrogen/deuterium at the cathode and oxygen at the anode. Pd is used because it absorbs hydrogen/deuterium avidly, thus bringing the atoms close together in its lattice (regularly spaced arrangement of atoms in the solid state).

Blank experiments gave a slightly negative rate of heat generation, on account of heat loss due to evaporation and so on. By contrast, the electrolysis of heavy water resulted in a positive excess rate of heat generation, this rate increasing markedly with current density I, at least as a function of I^2, reaching 100 Watt cm^{-3} at about 1A cm^{-2}.

Prolonged polarization of the palladium electrode in heavy water also resulted in bursts of high rates of heat generation, with the output energy exceeding the input by factors of 40 or more during the bursts.

The total specific energy output during the bursts as well as the total specific energy output of fully charged electrodes subjected to prolonged polarization was 5 – 50 MJ cm^{-3} (of electrode volume), and is 100 to 1 000 times the heat of ordinary chemical reactions.

But what exactly were the reactions?

One major factor contributing to the initial scepticism against nuclear reactions was that the excess energy released was not due to the established thermonuclear fusion reactions, which result in a tritium plus a hydrogen, or a helium plus a neutron. These reactions and the energies of the products are as follows:

$$^{2}D_{1} + {}^{2}D_{1} \rightarrow {}^{3}T_{1}\ (1.01\ \text{MeV}) + {}^{1}H_{1}\ (3.02\ \text{MeV}) \quad (2)$$

$$^{2}D_{1} + {}^{2}D_{1} \rightarrow {}^{3}He_{2}\ (0.81\ \text{MeV}) + n\ (2.45\ \text{MeV}) \quad (3)$$

Although low levels of tritium and, possibly, of neutrons were detected, the amounts could not account for most of the excess heat generated. (Nevertheless, some investigations have been more successful in finding tritium, which suggests that more than one reaction might have occurred.)

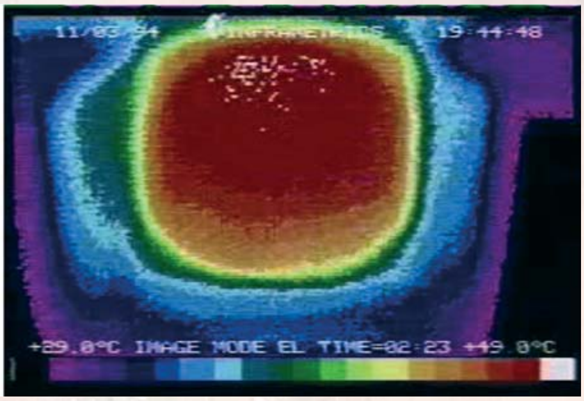


Figure 31.1 Infrared camera image of the cathode in an active electrolytic cell
The central red area with yellow and green borders is the hot cathode surrounded by cooler electrolyte solution; the white spots on the cathode are hot spots with temperatures off the top end of the scale (bottom of image); these hotspots are very dynamic flashing on and off from different parts of the electrode surface as can be seen in the video recording [9, 10].

The researchers experimented with different dimensions of electrodes and currents and recorded their results. The highest excess power generation achieved was 105 W cm^{-3} with the 0.1cm (thinnest) x 1.25 (shortest) palladium rod electrode run at 1.024 A cm^{-2}, and it happened at about 1 500 h after the start of the experiment.

The excess heat generated tended to go up exponentially with the current. There was a steady rate that appeared to increase slowly with time, with bursts of very high rates superimposed on the slowly increasing steady state. The bursts occurred at unpredictable times and were of unpredictable duration. Following such bursts, the excess heat production returned to a baseline, which could be higher than that prior to the initiation of the burst.

The heat produced was so great that the electrolytic cells were frequently driven to boiling point, when the rate of heat production became extremely large. It was not possible to make a quantitative estimate of the heat as the cells and instrumentation were unsuitable for making estimates under those conditions. Also, Fleishman and Pons adopted a policy of discontinuing the experiments (or at least reducing the current density) whenever the water started to boil. At such times, the palladium electrode also started to dissolve, which generated still more heat. They decided to avoid such conditions for fear of uncontrollable energy releases. These bursts of rapid increases of temperature were accompanied by marked increases in the rate of tritium (T) production, suggesting that the nuclear reaction(s) occurring were different from those in the steady state.

Indeed, T production has been observed by many other labs since, and is considered by some to be one of the strongest pieces of evidence for condensed matter nuclear science, as it suggests an entirely new mechanism whereby nuclear reactions could occur at low temperatures (see [7]).

Fleishman and Pons concluded in their 1990 paper co-authored with other cold fusion enthusiasts [3]: "It is our view that there can be little doubt that one must invoke nuclear processes to account for the magnitudes of the enthalpy [heat] releases."

Fleishmann and Pons' evidence for nuclear reactions was indirect, and depended on the excess heat generated that could not be explained by known ordinary physical or chemical process. No definitive nuclear products had been identified, and at the time, other investigators often had difficulty reproducing the results.

Since then, substantial progress has been made in the reproducibility of excess heat generation and in measuring nuclear products. The SPAWAR researchers are among the major groups that have carried out such experiments successfully.

THE SPAWAR REACTIONS

The research team led by Stanislaw Spzak and Pamela Mosier-Boss at SPAWAR used a modified procedure in which palladium and deuterium were deposited together on a cathode consisting of a thin metal film [6]. In 1995, they first found indications of nuclear activity when the electrolytic cell emitted X-rays with a broad energy distribution, and occasionally with well identifiable peaks. Tritium was detected sporadically and often at low rates. Nevertheless, there were active periods that persisted for days, with tritium produced at approximately 6 x 10^3 atoms/s.

Ten years later in 2005, they obtained further evidence of nuclear activity: heat generation, hot spots, mini-explosions (see Fig. 31.1), radiation, and tritium production. More importantly, they discovered that by placing the electrolytic cell in an external electrostatic field, the reaction(s) could be much speeded up, and new elements produced, among them Al, Si, and Mg (see [8]).

In a later report [9], Spzak and coworkers presented direct evidence of low-energy nuclear reactions in the Pd lattice and the emission of charged particles in amounts far greater than the background level. The density of tracks registered by the CR-39 detector, a simple piece of plastic placed next to the cathode, was "of a magnitude that provided undisputable evidence of their nuclear origin."

Under normal conditions when the cell operation is controlled by the cell current and temperature, the nuclear products consisted of X- and γ-rays, tritium, and excess heat. However, when the operating cell was placed in an external electric field, the reaction products included the formation of "new elements" as well as the emission of charged particles such as p+ (protons) and α^{2+} (alpha particles consisting of two protons and two neutrons).

Tracks can be recorded after only 1 h of exposure. The researchers suggest that 'coherent domains' are formed in the cathode shortly after activation by the external electric field, and these coherent domains correspond to the hotspots of nuclear reactions (see Fig. 1).

Although the nature of the nuclear reaction(s)

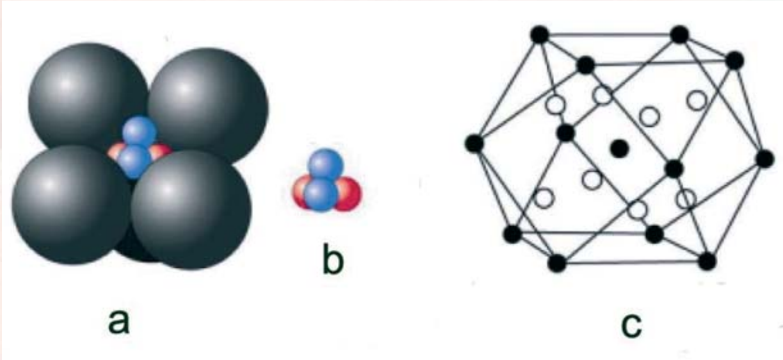


Figure 31.2 Proposed structure of pycnodeuterium in palladium lattice. (a) lump of deuterium atoms in an octahedral site between palladium atoms in host lattice, (b) lump of pycnodeuterium, (c) metallic deuterium lattice of pycnodeuterium (filled circles) forming a body-centred cuboctahedron structure

is still unclear, the emission of soft X-rays indicates that electron capture is occurring. The electron may be captured by a nucleus X, where X may be the deuteron (deuterium ion) D^+, a doubly charged deuteron D^{2+}, a lithium ion Li^+ (from the electrolyte) etc, with a neutrino ν escaping the reaction volume [8].

$$^{A}(X)_z + e^- \rightarrow A(X)z\text{-}1 + \nu \quad . (4)$$

The SPAWAR experiments are by no means the only replication of the Fleishman-Pons effect in the sense of nuclear reactions occurring in an electrolytic cell. The most notable feature about the effect is the heterogeneity of reactions, and the variety of conditions under which they happen.

EXCESS HEAT & HELIUM

One major product of cold fusion experiments involving deuterium appears to be helium, or helium-4, the usual abundant isotope. This was confirmed in three different sets of experiments conducted in another US Navy laboratory (NAWCWD) at China Lake, California between 1990 and 1994, funded by the Office of Naval Research [11]. There was a correlation between excess heat produced and the excess helium-4 measured in 18 out of 21 experiments. In experiments where no excess heat was generated, 12 out of 12 also produced no helium-4. This was a total of 30 out of 33 experiments that agreed with the hypothesis that the excess heat was correlated with producing helium-4. The measured rate of helium-4 production was always in the appropriate range of 10^{10} to 10^{12} atoms per second per Watt, in accordance with the reaction:

$$^{2}D_1 + {}^{2}D_1 \rightarrow {}^{4}He_2 + 23.8 \text{ MeV} \qquad (5)$$

When H_2O was substituted for D_2O, neither excess heat nor helium-4 was generated. However, the excess heat generated in the China Lake experiments was modest, and did not exceed 30 percent of input.

Several other groups have confirmed the production of helium-4 correlated with excess heat. But the most spectacular results came from the experiments of Yoshiaki Arata and Yue-Chang

Zhang at Osaka University, Japan [12].

Instead of a solid palladium cathode, Arata and Zhang used powdered palladium, or palladium black, which greatly increased the absorption surface area for deuterium. The palladium black was placed inside a container kept under a vacuum at constant temperature for 2-3 days before deuterium or hydrogen gas was injected at a constant low flow rate until the powdered palladium was fully saturated with the deuterium/ hydrogen.

Using palladium black with extremely small particle size (15 to 40 nm), a high fusion rate was obtained, amounting to >10^{15} $^4He_2$ atoms in the closed inner space of the cathode. In contrast, no $^4He_2$ (or excess heat) was ever generated when hydrogen was used instead of deuterium, or when bulk palladium was used.

Arata and Zhang also developed other materials that better absorbed H_2/D_2. In one experiment, Pd particles of 5 nm were embedded inside a matrix of ZrO_2. ZrO_2 on its own does not absorb H_2 or D_2, but ZrO_2-Pd easily absorbed about 3 D atoms per host Pd atom. Arata and Zhang proposed that the D atoms absorbed are effectively solidified as an ultrahigh density deuterium lump inside each octahedral space within the unit cell of the Pd host lattice. These "pycnodeuterium" (heavy deuterium) are dispersed to form a metallic deuterium lattice with body-centred cuboctahedron structure (see Fig. 31.2) [13].

Robert Duncan, a professor of physics and Vice Chancellor of Columbia university, New York, came away convinced that the excess energy produced is real, and that the research should be pursued

In a solid 'nuclear fusion reactor' using pycnodeuterium as fuel, the fuel sample was kept in an evacuated quartz glass cylinder chamber for two days at 130 ˚C. After that, D_2 gas was injected until pressure built up to 10 atm. Laser light was

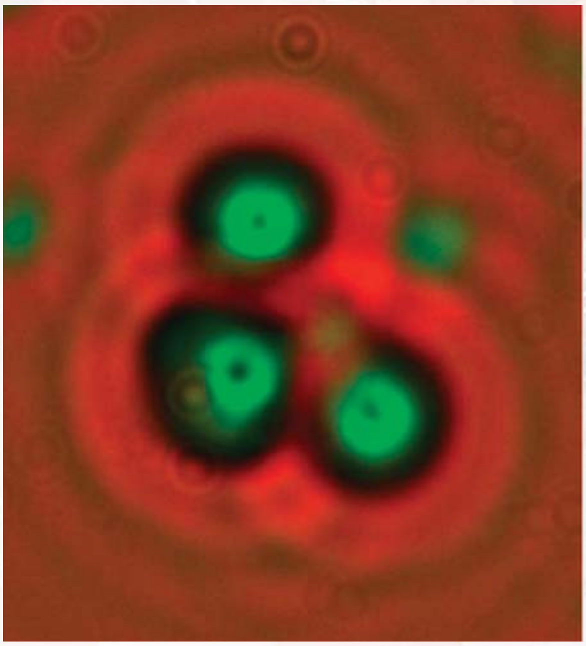


Figure 32.3 The tell-tale triple track of an energetic neutron [17]

then applied as a repeated rectangular pulse (20 pulse per second for 10 seconds) with pulse width of 2 ms (height of 7.5 kW, and pulse energy of 15 J/pulse).

Electron microscope pictures showed that after the 'laser welding' the ZrO_2 matrix and nano-Pd particles had melted, creating smooth spherical shapes as consistent with intense heat from nuclear reactions.

How well did the cold fusion reactor compare with hot fusion? It so happened that in 2002, laser stimulation had been used in hot fusion. With an extremely high power pulse of 10^{19} Watts/50 picosecond (10^{-12}s) applied to a plasma (hot ionised gas) at a temperature of 10^4 eV, a maximum of 10^{13} atoms of $^4He_2$ were generated per pulse.

In contrast, the laser welding nuclear fusion reactor of Arata and Zhang used 300 Watts, and generated 10^{19} to 10^{20} $^4He_2$ atoms per 10 seconds period of laser stimulation. The researchers own a patent on their reactor. At the International Conference on Cold Fusion which took place between 25 June and 1 July 2007, at Sochi, Russia, at least two different research groups reported replication of Arata and Zhang's results using a variant of the procedure that involved loading D_2 gas into nano-scale palladium black [14].

On 22 May 2008, Arata and Zhang performed a dramatic demonstration of the experiment in front of an audience of 60 that included physicists as well as reporters from 6 major newspapers and two TV studios [15]. When Arata injected the deuterium gas, the temperature rose to about 70°C, which Arata explained was due to nuclear and chemical reactions. When he turned the gas off, the temperature inside the cell remained warmer than the cell wall for 50 hours, which Arata said was an effect of nuclear fusion. At least one fellow physicist from Osaka University, Akito Takahashi, was impressed. "The demonstrated live data looked just like data they reported in their published papers." He said. "This demonstration showed that the method is highly reproducible."

In their latest publication, the SPAWAR team report finding a 'triple track' on their plastic detector, which they interpret as three alpha particles going out from a single point, a ^{12}C nucleus in the plastic breaking up into three equal parts (each an alpha-particle) having been struck by a very energetic neutron [16]. The energetic neutron was itself the result of a forced DD or DT fusion reaction within the Pd lattice (as envisaged by Arata and Zhang). The T, in this case, would have been formed by an earlier DD fusion.

In April 2009, Michael Mckubre, director of research at the Energy Research Centre of Stanford Research Institute in California, and one of the most respected cold fusion researchers, was featured in a CBS news programme [18]. As part of the investigation, the American Physics Society was asked to appoint an expert to review cold fusion research. They nominated Robert Duncan, a professor of physics and Vice Chancellor of Columbia university, New York. Duncan came away convinced that the excess energy produced is real, and that the research should be pursued. Subsequently, research grants were awarded to McKubre's team at Stanford and to the Naval Research Laboratory in Washington DC

32

TRANSMUTATION
THE ALCHEMIST DREAM COME TRUE

Not just base metals into gold, but the profuse creation of elements that's rewriting the book of genesis

Alien star chart by Li Poon

Cold fusion scientists have managed, not so much to transmute base metals into gold (although there have been unconfirmed reports to that effect), but more spectacularly, to make a whole range of elements on the lab bench, with equipment not much more sophisticated than what the ancient alchemists might have used. In the process, nuclear energy is released - safely and without toxic or radioactive wastes - that could be harnessed for heating or to generate electricity [1] (see Chapter 31).

In addition, there is the attractive possibility of solving the world's nuclear waste problem (see Box) by transmuting highly radioactive and toxic nuclear wastes from conventional nuclear reactors (see Chapters 3-7) into safer non-radioactive elements [2]. That topic will be dealt with in more detail in Chapter 35.

TRANSMUATIONS GALORE

Transmutation reactions come in two classes [5, 6]. The first class of reactions result in a large array of products with mass numbers spanning the periodic table; these may involve the formation of a heavy compound nucleus that decays and splits into different elements (but see later). The second class of reactions give distinct, isolated products directly.

These 'cold' or low energy transmutation reactions are remarkably easy to accomplish compared to the conventional 'hot' nuclear reactions that are supposed to take place in stars or supernova explosions, or else only at millions of degrees K.

By 2003, transmutation experiments had been studied in some detail by over 14 separate laboratories worldwide: Beijing University and Tsinghua University in China; Lab des Sciences Nucleaire in France; Frascati Laboratory and University of Leece in Italy; Hokkaido University, Mitsubishi Corporation, Osaka university, and Shizuoka University in Japan; SIA LUTCH, Tomsk Polytechnical University in Russia; Portland University USA, Texas A & M University, and University of Illinois Urbana-Champaign in the USA [5].

The minimum requirement for transmutation is a metal hydride film or membrane loaded up with hydrogen or deuterium to a high level, and kept in constant flux [5-8]. Electrode materials have ranged from carbon and nickel to uranium. The metal hydride can be loaded by electrolysis of water or heavy water using a thin film of the metal as cathode; or else deuterium gas can be made to diffuse through the metal membrane by injecting the gas on one side and evacuating from the other [9]. But a wide variety of experimental conditions have been used to trigger or speed up the reactions, including surface plasma electrolysis, plasma discharge, laser initiation and external electric or magnetic fields.

George Miley's team at the University of Illinois Urbana-Champaign in the United States is one of the main groups involved in transmutation [5]. They used multi-layer thin film nickel, palladium or titanium [6] coated by sputtering on polystyrene microspheres, and loaded up to a high level of hydrogen by packing the coated beads in the cathode of an electrolytic cell. The products of the nuclear reaction were documented carefully with a combination of secondary ion mass spectrometry (SIMS) and neutron activation analysis (NAA). SIMS detects most isotopes and is very sensitive but covers only a small area, typically a single microsphere, and is not very accurate. NAA on the other hand gives very accurate analysis of the entire electrode, but is restricted to detecting only certain elements. A combination of the two methods enabled the team to study a large number of isotopes. An overlap in the data set allowed a more accurate re-standardisation of the SIMS data to the more accurate NAA measurements.

A typical experiment is run continuously for 260 hours, resulting in a wide variety of elements. There are four high yield peaks in the atomic mass

THE WORLD'S NUCLEAR WASTE PROBLEM

The most pressing nuclear waste problem is the high level radioactive waste produced by nuclear reactors. It contains nuclear fission products and transuranic elements (with atomic numbers greater than uranium) generated in the reactor core, which have half-lives greater than 20 years, in some cases thousands, or tens of thousands of years [3].

The US Environment Protection Agency recognizes the ionising radiation from nuclear wastes as a serious health hazard [4]. Acute exposures result in radiation sickness, burns, premature aging, or even death. Cancers and birth defects result from stochastic exposure. Some radioactive waste elements, such as U-238, are both radioactive and highly toxic. U-238 has a half-life of 4.5 billion years.

Nuclear wastes also constitute a major security concern, as they could be acquired by terrorist organisations or rogue nations and turned into nuclear weapons.

It is estimated that high level nuclear waste is currently increasing by about 12 000 tonnes every year. Most of this waste is put into long-term storage after complicated treatments such as converting into glass or various concrete blocks. However, finding long-term storage sites that are safe and geologically stable remain a hot political issue in most countries.

DIRECT TRANSMUTATION OF SINGLE ELEMENTS

Yasuhiro Iwamura and colleagues at Mitsubishi's Advanced Technology Research Center and colleagues have taken another approach to nuclear transmutation by concentrating on the direct transmutation of one element into another [10, 11].

They used D_2 gas permeation through a sandwich of thin alternating layers of palladium (Pd) and CaO sitting on a bottom layer of bulk Pd. Deuterium is forced through the layers by exposing the top of the sandwich with a thin Pd film to D_2 gas while the bottom is maintained under vacuum. On the D_2 gas side, dissociative absorption causes the D_2 molecules to separate into D atoms, which diffuse though the sandwich towards the vacuum side, where they emerge from the Pd metal, combine and are released as D_2 gas (see Fig. 32.1). The element to be transmuted is deposited on the top Pd film of the Pd/CaO sandwich by electrolytic loading from a salt solution. Cesium (Cs), barium (Ba) and strontium (Sr) have been transmuted in this way. The analysis of elements was done *in situ*, without removing or disturbing the sandwich, using X-ray photoemission spectroscopy (XPS) directed at the topside of the sandwich

A typical experiment lasts for about a week or two. Cs has been transmuted into praseodymium (Pr) reproducibly in more than 60 experiments. Sr was transmuted into molybdenum (Mo) in three experiments lasting two weeks, the resulting Mo differed in isotope composition from natural Mo.

Based on an analysis of the depth profile of Pr, it appears that a very thin surface region of up to 10 nanometres is the active transmutation zone.

In the experiment involving transmutation of Ba to Sm (samarium), different isotopes of Ba resulted in the correspondingly different isotopes of Sm. ^{138}Ba transmuted into ^{150}Sm, and ^{137}Ba transmuted into ^{149}Sm, the increase in atomic mass was 12 in both cases, and atomic number 6. In both the transmutation of Cs to Pr and Sr to Mo, the increase in atomic mass was 8, and atomic number 4.

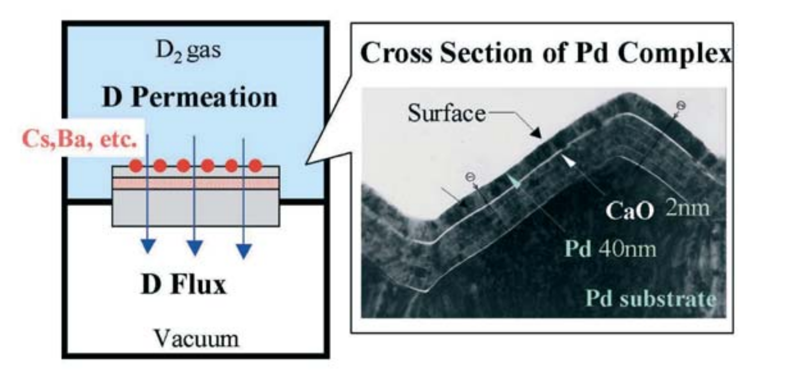


Figure 32.1 Transmutation by permeation (see text)

The most common products of conventional thermonuclear fusion are about 3 to 4 MeV, and that involves an enormous amount of energy input to accelerate apha particles to one-tenth the velocity of light. Iwamura's transmutation yields 50 to 67 MeV, with the greatest of ease, or very little energy input by comparison

The role of the CaO layer was revealed in an experiment in which Cs was transmuted to Pr [10]. In all three samples with the normal Pd/CaO sandwich, Pr was found as the end product, but not in an experiment without a CaO layer; nor in two experiments in which the CaO layer was replaced by MgO. The CaO layer appeared to increase the deuterium density 10-fold compared to palladium alone. The layer also has a very negative free energy, so that the transition metal Pd serves as a source of interface electrons to screen the positive charges of the deuterons from one another [12], thereby facilitating fusion and transmutation. It is thought that fusion may have occurred between deuterons to form helium, $^4He_2$, which then further fuses with the heavier nuclei to give the end product. This is compatible with the result obtained by Arata and Zhang (see previous Chapter).

Allen Widom and Lewis Larsen They suggested that the surface of metallic hydrides fully saturated with protons develops collective electron and proton surface plasma oscillations (plasmons) that enable the electrons to gain sufficient mass to be captured by protons resulting in ultra-low momentum neutrons. These ultra-low momentum neutrons could be absorbed (captured) by heavier nuclei to produce new elements across the Periodic Table

Laurence Hecht, editor of 21st Century Science and Technology commented that Iwamura's work implies a revolution in our understanding of the nucleus, a fundamental breakthrough in science, compared to which, practical applications, even one so necessary as a new supply of cheap, clean energy, is of secondary importance [13].

The most common products of conventional thermonuclear fusion are about 3 to 4 MeV, and that involves an enormous amount of energy input to accelerate apha particles to one-tenth the velocity of light. Iwamura's transmutation yields 50 to 67 MeV, with the greatest of ease, or very little energy input by comparison.

REWRITING CREATION

Allen Widom at Northeastern University Boston and Lewis Larsen of Lattice Energy LLC proposed a mechanism that could account for a wide range of fusion and transmutation reactions [7] (see Chapter 33). They suggested that the surface of metallic hydrides fully saturated with protons develops collective electron and proton surface plasma oscillations (plasmons) that enable the electrons to gain sufficient mass to be captured by protons resulting in ultra-low momentum neutrons. In a subsequent paper, they showed how these ultra-low momentum neutrons could be absorbed (captured) by heavier nuclei to produce new elements across the Periodic Table [14]. The expected chemical nuclear abundances resulting from such neutron absorption fit the available low energy transmutation experimental data quite well.

The important feature of such nuclear transmutations is that they do not need special mechanisms to penetrate the high Coulomb barrier, as proposed in other models.

First of all, the experimental distribution in atomic mass number A of the low energy nuclear reaction products measured in laboratory chemical cells are similar to the nuclear abundances found in our local solar system and galaxy. Furthermore, these maxima and minima in abundances resemble those predicted in the ultra-low momentum neutron absorption reaction cross-section (the likelihood of interactions), treating the neutron as a wave. This raises fundamental questions as to whether the conventional astrophysical account of how the elements are created in our stars and galaxies under thermonuclear conditions is correct.

The prediction based on treating the ultra-low momentum neutron as a wave results in a quasi-periodic curve: the peaks of reaction corresponds to the neutron wave fitting inside the spherical model potential wells of the nuclei, the radius of the well varying with atomic mass.

Data on the yields of transmutation product in an experiment using light water containing Li_2SO_4 in an electrolytic cell are plotted on the graph (see Figure 32.2). As can be seen, there is a reasonable correspondence between the experimental points and the predicted peaks and troughs of the neutron cross-section. The magnitude of the transmuted nuclear yields varies from one experimental run to another, but the agreement with the predicted curve remains over all experiments, and regardless of whether the electrode is titanium hydride, palladium hydride or layered Pd-Ni hydride.

When the neutron wavelength within the well

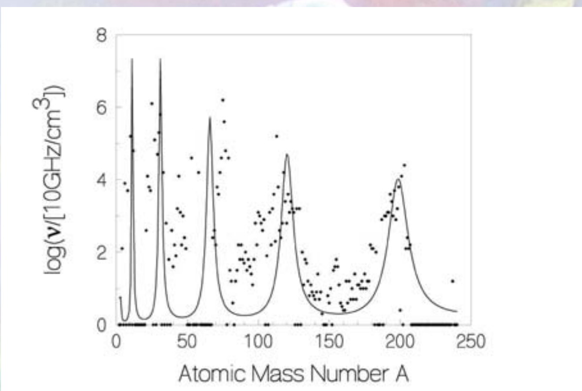


Figure 32.2 Experimental abundance of elements (filled circles) superimposed on neutron absorption cross-section as a function of atomic mass (continuous line)

reaches resonance with the radius of the well, a peak appears in the scattering strength. If we associate resonant couplings with the ability of the neutron to be virtually trapped in a region near the nucleus, then for intervals of atomic mass numbers around and under the resonant peaks, we could expect to obtain recently discovered neutron ‘halo’ nuclei (nuclei that have a clear separation between a normal core nucleus and a loosely bound low-density ‘halo’ of neutrons outside the core). The spherical potential well model predicts the stable regions for the halo nuclei and thus the peaks in observed nuclear transmutation abundances.

The neutrons yielding the abundances in our local solar system and galaxy have been previously assumed to arise entirely from thermonuclear processes and supernova explosions in the stars. These assumptions may be suspect in the light of the evidence from low energy nuclear reactions. Widom and Larsen remark: “It appears entirely possible that ultralow momentum neutron absorption may have an important role to play in the nuclear abundances not only in chemical cells but also in our local solar system and galaxy.”


POON

33

HOW 'COLD' FUSION WORKS

Many ways for atomic nuclei to come close and fuse in condensed matter

'COLD FUSION' WITH EASE

The surprising thing about cold fusion is how easily it could be made to happen, and in many different forms [1, 2] (see Chapter 32). This is in striking contrast to hot fusion, which requires temperatures of millions of degrees K.

The key to cold fusion is that it happens in condensed matter. Simply put, there are many ways for nuclei to come together coherently and fuse in condensed matter. Cold fusion is friendly fusion, and does not need to be forced by thermonuclear temperatures.

First of all, the hydrogen or deuterium nuclei are trapped in the host lattice, and hence much closer together than they would be in the gas phase. Under these conditions, quantum effects take over. Energy levels are no longer discrete; instead, they merge into broad bands. Coherent vibrations of the trapped nuclei, the electron cloud and the host lattice interact, all of which conspire to let nuclei slip under the Coulomb barrier and fuse together.

DELOCALISED OVERLAPPING WAVE FUNCTIONS

Retired physicist from the US Naval Research Laboratory Talbot Chubb describes cold fusion as using a "catalysed configuration" to replace the need for high-energy collisions between particles in hot fusion [3].

In the typical experiments where deuterium is absorbed or generated in a palladium electrode, the deuterons (nuclei of deuterium) become delocalised as waves with periods of the host lattice; this is referred to as a 'Bloch state'. Bloch states enable the waves of different deuterons to overlap, and at a certain point when the kinetic energy of the vibrations becomes greater than the potential energy of the Coulomb barrier, the latter becomes irrelevant and two deuteron waves fuse into one. The electrons will also be delocalised as Bloch waves and will serve to shield the like charges of the nuclei and enable them to come closer together, thus facilitating the fusion.

Two deuterons fusing together give helium-4, and excess energy of 23.8 MeV. The excess energy is transferred to the host lattice as phonons (sound waves) and dissipated as heat. This could explain the results of many cold fusion experiments, such as that of Arata and Zhang and perhaps that of Fleishmann and Pons that started the whole field (see Chapter 31).

However, it was already apparent in the Fleishmann and Pons experiments that excess heat was produced in at least two ways: a predictable steady state (when helium-4 could well be produced), and unpredictable bursts of intense activity associated with the production of tritium.

The key to cold fusion is that it happens in condensed matter. Simply put, there are many ways for nuclei to come together coherently and fuse in condensed matter

ELECTRON CAPTURE FOR TRANSMUTATION

Allen Widom at Northeastern University Boston and Lewis Larsen of Lattice Energy proposed a mechanism that could account for a wide range of fusion and transmutation reactions, electron capture by protons or deuterons [4].

In nuclear physics, it is very well known that a proton can capture a negatively charged lepton (light particle) and produce a neutron and a neutrino, and a common form of nuclear transmutation in condensed matter can be understood in term of this reaction.

An electron that wanders into a nucleus with Z (atomic number) protons and N (= A (atomic mass) – Z) neutrons can be captured, producing a neutrino and leaving behind a nucleus with Z-1 protons and N+1 neutrons. There is no Coulomb barrier in this process, which makes it much more likely than other reactions. In fact, a strong Coulomb attraction between an electron and a nucleus favours electron capture for nuclear transformation.

While lepton capture is known to occur in the case of muons (a kind of lepton) mixed into hydrogen systems, it is regarded as difficult for electrons to be captured by protons. For the reaction to happen, the lepton must be sufficiently massive. The muon is more than sufficiently massive to be captured by the proton, but not the electron, which needs to be at least 2.531 times as massive.

However, the electron mass in condensed matter can be modified by local electromagnetic field fluctuations. For example, laser light fields can "dress" an electron with additional mass. The surface states of metal hydrides are very important in this respect.

Alien star chart by Li Poon

Collective surface oscillations of charged ions are involved in the weak interactions responsible for electron capture in condensed matter. The radiation frequencies of these oscillation range from the infrared to the soft X-ray spectras. The surface protons are oscillating coherently, contributing to the large magnitude of electromagnetic fluctuations. The neutrons produced by electron capture have an ultra low momentum (with long wavelength) due to the size of the coherence domain of the oscillating protons, estimated to vary from about one to ten microns in length. The long final state neutron wavelength allows for a large neutron wave function overlap with many protons, which increases the coherent neutron production rate.

It is estimated that the electron mass enhancement due to the electromagnetic field fluctuations (collective proton oscillations) on the surface of palladium hydride is about 20.6 fold, which is much more than enough for electron capture by proton or deuteron. The proton field oscillations can be amplified by shining a laser light on the palladium surface, which can enhance the production of neutrons that in turn catalyse other reactions.

The neutron, n, can fuse with other nuclei in transmutation reactions. Lithium (Li) is present in the electrolyte. A Li ion near to the hydride (electrode surface) could initiate a chain of reactions as follows:

$$^{6}Li_{3} + n \rightarrow {}^{7}Li_{3} \qquad (1a)$$

$$^{7}Li_{3} + n \rightarrow {}^{8}Li_{3} \qquad (1b)$$

$$^{8}Li_{3} \rightarrow {}^{8}Be_{4} + e^{-}\text{ (electron)} + v\text{ (neutrino)} \qquad (1c)$$

$$^{8}Be_{4} \rightarrow {}^{4}He_{2} + {}^{4}He_{2} \qquad (1d)$$

$$Q \sim 26.9\text{ MeV}$$

A large amount of energy, 26.9 MeV is generated by this chain of reactions.

Having produced $^{4}He_{2}$, further neutrons may react to build heavy helium isotopes, and regenerate Li as follows.

$$^{4}He_{2} + n \rightarrow {}^{5}He_{2} \qquad (2a)$$

$$^{5}He_{2} + n \rightarrow {}^{6}He_{2} \qquad (2b)$$

$$^{6}He_{2} \rightarrow {}^{6}Li_{3} + e^{-} + v \qquad (2c)$$

$$Q \sim 2.95\text{MeV}$$

Other possibilities include direct lithium reactions

$$^{6}Li_{3} + n \rightarrow {}^{4}He_{2} + {}^{3}H_{1} \qquad (3a)$$

$$^{3}H_{1} \rightarrow {}^{3}He_{2} + e^{-} + v \qquad (3b)$$

$$Q \sim 4.29\text{ MeV}$$

These examples show that a final product, such as $^{4}He_{2}$, does not necessarily constitute evidence for the direct fusion of two deuterons, which requires tunnelling through a high Coulomb barrier (see above). More importantly, final products such as helium^{-3} and tritium are also possible, as have been detected in many experiments.

The above reactions may be involved in transmutations in electrolysis systems that have Li salts, but does not account for the formation of helium in the apparatus such as that of Arata and Zhang (see Chapter 31) that has no electrolyte at all, and where deuterium is loaded directly onto palladium. The SPAWAR group which does use an electrolysis system [5], found that energetic neutrons capable of splitting carbon into three equal parts, are created, only if palladium is present, and Li does not appear to be involved. Widom and Larsen's theory does not predict energetic neutrons. On the contrary, it predicts the production of ultra low energy neutrons (see Chapter 34).

Widom and Larsen are latecomers to the cold fusion field, and it is not clear to what extent their theory is accepted. I find it quite convincing especially for the transmutation of elements [2], though it doesn't necessarily exclude other mechanisms that depend equally on quantum coherence in condensed matter. In the final chapters of this volume, Larsen will elaborate and defend their theory, which differs from both conventional nuclear fission and the cold fusion proposed by others in the community.

LOCHONS

Krit Prasad Sinha and Andrew Meulenberg at the Indian Institute of Science Banagalore propose the formation of deuteride or hydride (D^{-} or H^{-}) ions due to interactions of the deuterium or hydrogen with the phonon vibrations of the host lattice. 'Local charged bosons' (lochons) or local electron pairs can form on D^{+} to give D^{-} [6-8].

At the same time, the collective motion of the deuterons driven by the phonons can introduce 'breathing' modes in the Pd lattice. If these breathing modes are resonant with the deuteron motion, they enhance deuteron migration and the rapid refilling and regeneration of the active sites. If the resonant vibration is anti-phase, the Pd atoms could move apart as adjacent deuterons come together, thus allowing direct collision of the deuterons while an electron cloud helps screen the repulsion due to the deuterons' positive charges.

The formation of D^{-} reverses the normal electrical repulsion between D^{+} ions, as D^{-} and D^{+} can attract each other. The $D^{+}D^{-}$ equilibrium positions in the lattice are much closer together than in free molecular D_{2} because of the increased effective electron mass from phonon interaction, reducing the electron distribution size into the sub-nanometre range, and therefore the point at which the attraction begins to diminish. The paired $D^{+}D^{-}$ system has a much reduced zero-force distance (~2 nm) relative to that of a D_{2} molecule (~7 nm). All these mechanicsms conspire to increase the probability of fusion.

The D^{-} and D^{+} fuse to form $^{4}He_{2}$ releasing a large amount of energy, 23.8MeV, which is carried by the alpha particle and the ejected electron pair. Sinha and Meulenberg calculated a reaction rate of about 1.5 x10^{11} s^{-1}. This is comparable to the muon-catalysed reactions giving tritium plus proton (T + p) or ^3He + n processes (see above).

This mechanism too, could be greatly enhanced by laser stimulation.

SELECTIVE RESONANT TUNNELLING

In November 1989, the Energy Research Advisory Board of the Department of Energy in the United States made five recommendations, among them, to check for excess tritium in the electrolyte in which cold fusion was supposed to have occurred. However, the amount of tritium generated did not tally with neutron emission. The expected 14 MeV neutron was not detected.

But tritium has appeared since in experiments in Japan, Italy, Russia, USA, Canada, India and China, and according to Li Xing Zhong at Tsinghua University Beijing China, it is one of the strongest pieces of evidence for condensed matter nuclear reactions, as it implies a new mechanism operating at low energy: selective resonance tunnelling [9].

A harmonic circuit is able to pick up the specific frequency from the air, but when the signal is weak, the resistance of the circuit must be low. It is the same with resonance tunnelling of the Coulomb barrier. At low energy, the Coulomb barrier is thick and high, hence the incident deuteron wave in the nuclear well is very weak. The amplitude of the weak penetrating wave may be enhanced by the resonance effect when the phase of the reflected wave inside the nuclear well is the same as that of the incident wave. This is resonant tunnelling. The damping must be weak, which is due to the fusion reaction itself, because the deuteron wave function disappears on fusion. Thus, this fusion reaction rate cannot be very fast, or it will kill the resonant effect. On the other hand, the rate cannot be too small, or it will give no fusion. As a result, the life-time of the deuteron wave function cannot be too large or too small. There is an optimum τ life to match a specific Coulomb barrier.

$$\tau \text{ life} \sim \theta^2 \tau \text{ flight} \qquad (4)$$

θ is a very large number for a thick and high Coulomb barrier, of the order of 10^{22} to 10^{31} or greater here. ($1/\theta^2$ is the 'Gamow penetration factor', the kinetic energy of the approaching nuclei relative to the energy of repulsion between the nuclei); τ flight is the flight time inside the nuclear well for the penetrating deuteron, and is of the order of 10^{-23}s.

The reason there is no neutron emission from resonant tunnelling at low energy is because the lifetime for a neutron emission process is too short at around 10^{-23} s. Only the weak interactions (β - decay or κ - capture, loss or gain of electron) might possibly provide the lifetime necessary.

Thus, selective resonant tunnelling provides the mechanism for penetrating the Coulomb barrier, and its selectivity explains why there are no neutron or gamma radiations after the resonant tunnelling at low energy.

If weak interaction is the only possible reaction for the resonant tunnelling at low energy, the possible reactions are between a proton p and a deuteron d:

$$p + d \rightarrow T + e^+ \text{ (positron)} + \nu \qquad (5a)$$

$$p + d \rightarrow T + \nu \qquad (5b)$$

κ capture

Usually the positron decay is faster than κ-capture, the capture of an electron. In the case of resonant tunnelling, positron decay is too fast to meet the matching condition, so only κ-capture is possible. This is consistent with experimental results. The annihilation of positron would produce 0.511MeV gamma radiation. But this is not observed in any tritium production experiments. The hydrophilic nature of the heavy water might explain the contamination by light water in the electrolytic cells, and that would be the source of protons for the resonant tunnelling reactions.

Solid state provides an energy band for deuterons or protons, thereby increasing the possibility of overlap with the resonant tunnelling state. Certain metals (Pd, Ni, Ti etc.) are particularly good because of their ability to absorb hydrogen, thereby filling this energy band to capacity.

Tritium is one of the strongest pieces of evidence for condensed matter nuclear reactions, as it implies a new mechanism operating at low energy

34

NUCLEAR ENERGY ON TAP?

How weak interactions can provide safer, cleaner nuclear energy and revolutionize the energy industry

Dragon nursery by Li Poon

Existing nuclear power generation depends on 'strong interaction' that splits atoms. The technologies were directly derived from nuclear physicist Enrico Fermi's experimental work in Chicago, USA, in the 1940s [1]. Thanks to the unfortunate legacy of World War II and the US Manhattan Project to secretly build the atom bomb, today's commercial nuclear power generation and fuel cycles [2] have always been intimately interwoven with nuclear weapons.

In contrast, Low Energy Nuclear Reactions (LENRs), which emerged from 'cold fusion' [3] (see Chapter 31) are a revolutionary new primary energy source. If successfully commercialized, LENRs could potentially herald in a new age of affordable, clean and safe energy, in contrast to power generation by current nuclear fission technologies (see Chapters 3-7)

Being nuclear, LENRs could potentially improve by many orders of magnitude the density and longevity of energy storage compared with existing technologies such as chemical batteries and electrostatic capacitors, and provide a vast array of cost effective, scalable, portable, and distributed power generation systems that could be deployed throughout the world.

Research and development on LENRs is quietly being pursued by companies and a small scientific community in the US, Russia, China, Japan, Italy, France, and Israel. Recently, there have been indications that India may restart its basic R&D efforts in this area [4].

LENR NOT COLD FUSION

In a hastily scheduled television news conference held in March 1989 [5], Pons and Fleischmann (P&F) reported experiments with ordinary electrochemical cells filled with deuterium (D) in which they claimed to have observed rates of excess heat production so very high that they could only have been the result of nuclear process [3]. P&F proposed some sort of 'cold' D-D fusion reaction [6].

I believe P&F's speculative conclusion about fusion being responsible for the unusual amounts of excess heat was wrong, although they were right about the excess heat being the result of a nuclear process, but it came from weak interactions [7], unbeknownst to them or anyone else at the time.

LENRs comprise a complex, interrelated family of nuclear phenomena that fundamentally differ from fission (violent splitting of heavy atoms) and fusion (fusing together of light atoms, such as in stars), which are what most people are familiar with in connection with nuclear reactors and military weapons.

Collective weak interaction LENRs can occur at the interface between the chemical and nuclear energy realms. In condensed matter systems, nanoscale many-particle collective effects enable certain nuclear reactions to take place at ordinary temperatures and pressures.

Beginning in May 2005, Allan Widom at Northeastern University and Lewis Larsen at Lattice Energy LLC have made a series of theoretical breakthroughs that, for the first time, explain the physics underlying a large body of experimental anomalies observed by scientists for 100 years. This body of work has become known as the Widom-Larsen theory of LENRs [8 – 14].

Unlike the somewhat ad hoc theoretical ideas advocated by cold fusion theorists for many years, our work is anchored in the 'bedrock' of electroweak theory within the framework of Standard Model. It weaves together all the previously disparate threads of experimental evidence into a coherent whole using rigorous, established, well-accepted physics and collective effects.

Collective weak interaction LENRs can occur at the interface between the chemical and nuclear energy realms. In condensed matter systems, nanoscale many-particle collective effects enable certain nuclear reactions to take place at ordinary temperatures and pressures

WIDOM-LARSEN THEORY PREDICTS ULM NEUTRONS

The Widom-Larsen (W-L) theory explains low energy nuclear reactions (LENRs) in terms of the production of neutral subatomic particles called "neutrons" at ordinary temperatures and pressures. Unlike conventional neutron-triggered fission and hot fusion reactions (that involve random collision of individual particles and require extremely high temperatures and pressures), the W-L theory proposes that collective processes involving many particles acting in concert to generate neutrons with negligible kinetic energies, i.e., they have 'ultra low momentum' (ULM) [15] (see Chapter 32).

Such neutrons are created within collectively oscillating patches of protons or deuterons (found on surfaces of hydrogen-loaded metallic hydrides) that can react directly with heavy-mass electrons created by the huge local nanoscale electric fields that also occur on the hydrogen-coated metallic surfaces. In such nanoscale surface environments, neutrons are created collectively in a weak interaction process directly from electrons (e^-) and the nuclei of hydrogen, i.e., protons (p^+) and/or deuterium, deuterons (d^+), as follows [8]:

$$e^- + p^+ \rightarrow \text{neutron} + \text{neutrino} \qquad (1)$$

$$e^- + d^+ \rightarrow 2\ \text{neutrons} + \text{neutrino} \qquad (2)$$

This type of neutron production due to weak interactions in very high surface electric fields is well-described by the generally accepted electroweak theory [16] on which the W-L theory of LENRs is based.

An isolated 'normal' thermal neutron outside a nucleus travelling through a solid has a quantum mechanical wavelength of about 0.2 nanometre (1 nanometre is 10^{-9}m) and a speed of about 2 200 metres per second, which is faster than a rifle bullet. Interestingly, the 'size' of a neutron confined *inside* an atomic nucleus is even smaller, several femtometres (10^{-12} m).

In contrast, an ULM neutron formed on a metallic hydride surface in a LENR is more or less standing still. Being formed collectively, ULM neutrons have almost no kinetic energy at the instant of their creation. This gives them huge quantum mechanical wavelengths compared to 'normal' neutrons. ULM quantum mechanical wavelengths (conceptually, effective 'size') increase dramatically [8]. *Note that ULM neutrons have much smaller energies (and correspondingly larger quantum mechanical wavelengths) than even the 'ultracold' neutrons* [17] produced so far in certain experiments.

The 'size' of ULM neutrons is typically extremely large in comparison to thermal neutrons.

It is directly determined by the spatial dimensions of the surface 'patch' of protons or deuterons in which they were created. In particular, their wave function must span the entire patch. Therefore, on the surfaces of condensed matter (e.g., a metallic hydride), the wave functions of ULM neutrons can easily reach 20 – 30 microns, i.e., 10 000 to 15 000 times that of thermal neutrons; and roughly the size of a large bacterium or a cell. Surfaces of hydrogen-loaded metallic hydrides are one of the few environments in the universe where subatomic neutrons become almost microscopic.

TRANSMUTATION BY ULM CAPTURE

At a 'size' of 0.2 nanometre, a thermal neutron can interact only with just a few atoms at any given instant; and it is also moving fast. In contrast, the gigantic ULM neutrons can interact collectively with literally thousands of nearby 'target' atoms all at once. This unique property increases the probability of their being absorbed by those nearby atoms to nearly 100 percent. A nuclear physicist would say ULM neutrons have phenomenally high "absorption cross-sections."

ULM neutrons' huge size is exactly why biologically dangerous energetic ('hot') neutrons are not released by LENR systems. ULM neutrons are extraordinarily 'cold' to begin with; and virtually all are absorbed locally; they never get a chance to escape and go anywhere. It is the first reason why LENRs are safe and environmentally friendly compared with heavy element neutron-triggered fission and light element hot fusion (but see SPAWAR experiment at the end of Chapter 31).

After being created, ULM neutrons are efficiently absorbed by nearby target atoms, resulting in nuclear transmutations into different elements or isotopes [18]. Unstable transmutation products undergo subsequent weak interaction beta decays [19] (with release of electron) that, depending upon exactly which nearby target elements were used as 'fuel,' can release large amounts of nuclear binding energy [20].

Another reason why LENRs are environmentally friendly is that *extremely neutron-rich*, very unstable intermediate transmutation products turn into stable, non-radioactive elements very quickly via cascades of rapid beta decays. Such neutron-rich intermediate nuclear products have short half-lives, of milliseconds, seconds, minutes, or at most hours; and typically not even days or months, let alone years. That is why LENR systems do not produce large quantities of long-lived hot radioactive isotopes like today's commercial fission reactors. As a result, there are no known nuclear waste disposal issues with LENR systems. Long-lived, highly radioactive isotopes (gamma emitters like cobalt-60) are not produced in detectable quantities; this has been verified in many LENR experiments.

The W-L theory also explains why hard gamma and X-rays are not released during LENR system operation [9]. This arises from unique heavy-mass electrons created by the very strong nanoscale electric fields that occur in regions above localized patches of collectively oscillating protons and deuterons where neutron production and absorption are taking place. Unlike isolated normal-mass electrons situated in a vacuum or a hot plasma, heavy-mass electrons created in condensed matter LENR systems can directly absorb a hard gamma or X-ray photon, "ring like a bell" for an infinitesimal fraction of a second, then (according to conservation of energy) reradiate a much larger number of much less energetic photons (mostly in the infrared region, with a much smaller 'tail' of soft X-ray photons).

In operating LENR systems, therefore, hard gamma ray photons in an energy range between 0.5 MeV and 10.0 MeV (often created during absorption of ULM neutrons by some, but not all, atoms/isotopes) are locally absorbed by heavy-mass electrons before they can escape [8]. Those electrons then convert the absorbed gammas directly into raw heat in the form of benign infrared photons that are also locally absorbed. LENR systems have what amounts to built-in gamma shielding during operation, a remarkable property by any standard.

A gamma-absorbing 'patch layer' of heavy-mass electrons in an LENR system has the ability to stop a very dangerous (~5 MeV) gamma ray in less than two nanometres. Whereas it would take ~10 cm of lead, ~25 cm of steel, or ~1 metre of very heavy concrete to accomplish the same degree of protection against 'hard' gamma radiation [21].

WEAK INTERACTION TRANSMUTATION & CLEAN ENERGY

A key difference between LENRs and fission or fusion technologies lies in the fact that LENRs involve very large emissions of neutrinos [22], a ghostly, massless type of photon (i.e., light) that can carry substantial energy but barely interacts with ordinary matter (which is why you can't see them like visible light). An energetic neutrino can pass through a billion miles of lead with very little chance of being absorbed. Generally speaking, a nuclear reaction in which neutrinos are either emitted or absorbed involves what physicists call "weak interaction".

In beta-decay, a type of weak interaction [19], a neutron (with no net electric charge) located inside an unstable atomic nucleus spontaneously breaks up into a positively charged proton, which remains inside the nucleus, plus an energetic negatively charged electron that escapes the nucleus as a beta particle, and a neutrino photon that flies off into space. As the nucleus of the atom undergoing beta decay suddenly contains one more new proton, its atomic number increases by +1 which means that the atom is now a different element. Mediated by one or more intermediate beta decays, transmutation reactions eventually produce stable, non-radioactive isotopes of different elements. A sequence of beta decays immediately followed by successive rounds of neutron absorption produces progressively heavier elements; astrophysicists believe that most elements found in the periodic table were originally created by that process in stars [23].

Collective weak interaction transmutation reactions can be used to deliberately transmute one element into another; this can be commercially valuable for producing certain rare elements/ isotopes from more common ones. However, what is potentially vastly more valuable to society is that 'ultracold' (low energy) neutrons uniquely produced in certain LENR weak interactions can be used to trigger the release of stored nuclear energy from target fuel atoms on demand. This capability creates an opportunity to develop an entirely new nuclear power technology that is much cleaner and safer than the old.

In weak interaction LENRs, excessive nuclear binding energy is to a degree 'bled-off' in the form of emitted neutrino photons, containing substantial amounts of energy in a completely benign form, the neutrino itself, which just flies off into space without interacting with local matter. In contrast, fission and fusion processes involve 'strong interaction' in which all of the nuclear binding energy released is channelled directly into various non-neutrino highly energetic products: charged electrons and alpha particles; uncharged neutrons; hard' (very energetic) gamma/X-ray photons [24]; and 'hot' (highly radioactive), comparatively long lived isotopes. All of these strong interaction fission and fusion products can readily interact with matter, including living organisms. Energetic neutrons and gammas/X-rays are one reason why radiation containment structures for commercial fission reactors often have walls consisting of 1 metre thick reinforced concrete and 25 cm thick special steel plates [25] (see Chapter 4).

Energetic neutrons, which are ~1 839 times as heavy as beta particles, can deeply penetrate solid objects, potentially creating induced radioactivity when they are finally 'stopped' and absorbed by atoms..

Energetic 'hard radiation' photons (X- and gamma-rays) can knock electrons out of atoms, causing local ionization. Modern electronics can be damaged or destroyed by such ionization events. In living organisms, absorption of energetic 'hard' photons creates ionization, breaks chemical bonds, damages DNA, and generally wreaks havoc with biochemical reaction networks.

LENR CLEAN ENERGY ON TAP

Commercial LENR-based power generation systems could be developed with unprecedented levels of energy density, longevity, and scalability. Such systems might eventually allow a car or an airplane to travel around the world without refuelling. They would create true energy independence, breaking oil's stranglehold on the global economy.

LENRs will probably first enter the commercial market as small scale, integrated battery-like portable power sources and small backup power generation systems for residential homes or remote facilities, with electrical outputs ranging from under 100 W to 1-5 kW. These could then be scaled-up and rapidly applied to the development of much more powerful heat sources and power generation systems based on different types of LENR target fuels and energy conversion technologies. At system power outputs of just 5-10 kW LENR-based distributed power generation systems could potentially satisfy the requirements of most urban and rural households and smaller businesses worldwide.

At electrical outputs of just 50-200 kW, LENR-based systems could begin to power vehicles, breaking the stranglehold of oil on transportation, and giving new-found 'energy sovereignty' to many countries.

While entirely new types of large, LENR-based power plants could be designed and built from scratch, it would make greater economic sense to scavenge coal-fired power generation infrastructure as much as possible. Analogous to retrofitting new LENR-based cores in existing fission power plants, boilers in coal-fired power plants could simply be retrofitted with LENR-based boilers using lithium as target fuel, for example. This could eliminate carbon emissions from retrofitted plants while continuing to supply low-cost electricity to regional grids all over the world.

Commercial LENR-based power generation systems could be developed with unprecedented levels of energy density, longevity, and scalability. Such systems might eventually allow a car or an airplane to travel around the world without refuelling

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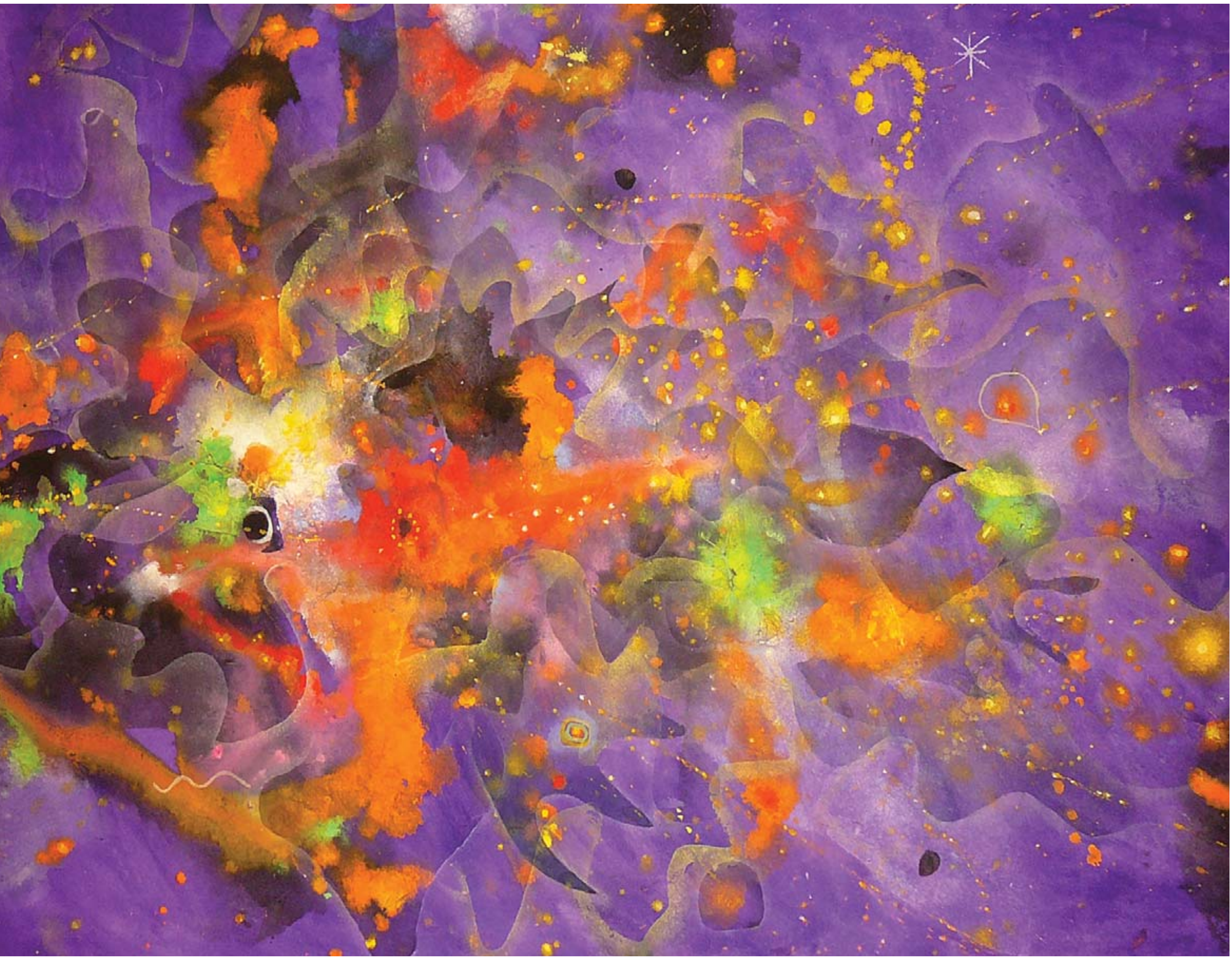
NUCLEAR WASTE DISPOSAL?

How weak interactions can transform radioactive isotopes into more benign elements



Phoenix 1 by Li Poon

NUCLEAR WASTES PILE UP

The vast bulk of the world's radioactive waste is created in uranium-based commercial fission reactors [1]. While some of that waste exists in the form of radioactive isotopes of gaseous elements and reactor components that have become radioactive from exposure to fast reactor fission neutrons, most nuclear waste is created and remains in reactor fuel rods [2] and related fuel assemblies where the raw nuclear heat for power generation is produced by nuclear fission reactions.

In spontaneous or neutron-triggered fission (in which an unstable fissile atomic nucleus absorbs a neutron), a heavy nucleus (e.g., uranium with atomic mass A = 235) violently splits apart into two 'daughter' nuclei; each fragment flying off with huge amounts of kinetic energy that creates intense heat when the fragments collide with surrounding materials in fuel rods [2, 3] . The fission process is asymmetric (the two daughter products almost always have unequal masses); also, it does not fragment exactly the same way every time, so a complex array of fission products with a broad range of many different masses is produced. While this fission product array includes virtually every element from zinc through the lanthanides, it is actually concentrated into two characteristic mass peaks: one from A = ~90 to 105 and a second from ~135 to 145 [4].

Unstable radioactive isotopes of the elements strontium (Sr), zirconium (Zr), technetium (Tc), and cesium (Cs) comprise perhaps the most abundant fission products produced in typical commercial reactors [4]. Other unstable fission products are also typically neutron-rich, and many (but not all) decay very rapidly via weak interaction beta processes (transmutation reactions) that may or may not be accompanied by gamma radiation emission. Different radioactive isotopes decay at different rates (half-lives), becoming stable, benign, non-radioactive isotopes over time. However, certain radioactive 'hot' isotopes with long half-lives remain biologically hazardous for many thousands of years.

In most present-day uranium fission reactors, roughly 25 percent of the U-235 originally present in the fuel rods when they were first loaded into the reactor still remains unburned when fuel rods reach the point at which they have accumulated enough 'neutron poisons' inside them that they cannot sustain a fission chain reaction. They are then considered 'spent' fuel rods.

In countries with 'once through' nuclear fuel cycle policies, spent fuel rods are simply removed from reactors, isolated in nearby 'cooling ponds' until their level of radioactivity decreases, and then ultimately shipped to a secure long term storage site (e.g., Yucca Mountain, Nevada, in the US). The 'once through' countries presently include the US, Canada, Sweden, Finland, Spain, and South Africa. The rest of the world uses some form of reprocessing of spent nuclear fuel in which "cooled" fuel rod assemblies are transported to strategically located reprocessing centres in which plutonium and uranium are separated from other materials and subsequently reintroduced into the

Materials Commonly Found In Spent Fuel Rods		Properties					
Type	Element/Isotope	Half-Life (~ years)	Fission Yield ~ %	Normal Decay Mode	Thermal Neutron Capture Cross Section (barns)	Fission or Beta-decay Gammas?	Q-value for Beta Decay or Fission (MeV)
Fissile Fuels	Uranium U-233	159,000	NA	alpha	531 (fission)	Y	~190 (fission)
	Uranium U-235	704 million	NA	alpha	582 (fission)	Y	~190 (fission)
	Plutonium Pu-239	24,000	NA	alpha	752 (fission)	Y	~200 (fission)
Fertile Fuels	Uranium U-238	4.5 billion	NA	alpha	2.7	N	NA
	Thorium Th-232	14 billion	NA	alpha	7.4	N	NA
Rod Cladding	Zr (5 isotopes)	NA - stable	NA	NA	0.01 to 1.2	N	NA
	Iron (5 isotopes)	NA - stable	NA	NA	1.3 to 2.7	N	NA
Long-lived Fission Products	Cesium Cs-135	2.3 million	6.9	Beta	8.9	N	0.269
	Technetium Tc-99	21,000	6.1	Beta	2.3	N	0.294
	Zirconium Zr-93	1.53 million	5.5	Beta	2.7	Y	0.091
	Palladium Pd-107	6.5 million	1.3	Beta	1.8	N	0.033
	Iodine I-129	15.7 million	0.8	Beta	20.7	Y	0.194
Medium-lived Fission Products	Cesium Cs-137	30	6.1	Beta	0.25	Y	1.2
	Strontium Sr-90	29	5.8	Beta	0.0097	N	2.8
	Samarium Sm-151	90	0.5	Beta	15200	N	0.077
	Krypton Kr-85	10.8	0.2	Beta	1.7	Y	0.687

Data compiled by Lattice Energy LLC; note that values found in different data sources are not entirely consistent with each other. The most worrisome items are highlighted in yellow

Table 35.1 Properties of material commonly found in spent fuel rods nuclear fuel cycle. The remaining presently unusable isotopes from reprocessing spent fuel rods are then shipped to permanent nuclear waste storage facilities.

The whole issue of nuclear waste storage and reprocessing is highly controversial, raising serious questions on safety, sustainability, nuclear proliferation and economy [5] (see Chapter 5)

DEADLY ARSENAL OF FISSON WASTES

Common elements and fission products/isotopes found in spent fuel rod assemblies from commercial fission power plants are presented in Table 35.1.

From the standpoint of nuclear proliferation and radioactive waste, the most troublesome or hazardous materials commonly present in spent fuel rods include: U-233, U-235, Pu-239, Cs-135, Tc-99, Zr-93, Cs-137, and Sr-90. Radioactive caesium and strontium isotopes are particularly dangerous to vertebrates because, if they enter the food chain they can substitute chemically for calcium, thereby accumulating in calcium-rich bone material where they gradually decay, irradiating and damaging vital marrow cells. And this can severely depress the immune system.

'Fertile' isotopes such as U-238 and Th-232 can absorb neutrons without fission and, through a series of transmutation reactions, produce fissile Pu-239 and U-233 respectively.

LENR-based nuclear waste remediation techniques would entail a multi-step process of transforming entire spent fuel rod assemblies into specific types of nano-particulate targets with high surface-to-volume ratios that would enable them to come into close contact with locally generated LENR ULM neutrons and become transmuted into stable, and much less toxic elements

LENR SLOW NEUTRONS READILY CAPTURED

A comparatively 'slow' 0.025 eV thermal-energy neutron moves at a speed of 2 200 metres/second [6]. By contrast, 'fast' 2 MeV neutrons produced in fission chain reactions travel at speeds a few percent of the speed of light. Regarding total neutron absorption cross sections (measured in "barns" - a barn is an area of 10-24 cm2), fissile materials such as U-233, U-235, and Pu-239 (along with many other, but not all, non-fissile isotopes) follow the low-energy region 1/v rule [7], v being the velocity of neutrons measured in metres per second. This means that the lower the velocity of an incident colliding neutron, the higher its absorption (capture) cross-section. Neutron absorption by 1/v isotopes is therefore much more efficient with slow neutrons than with fast ones; *the slower the better.* Importantly, *ultra low momentum (ULM) neutrons created in certain low energy nuclear reactions (LENR) environments have kinetic energies that are vastly lower than those of thermal neutrons*. Compared to speedy thermal neutrons, collectively created ULM neutrons are born almost 'standing still'. This means that their capture cross-sections on 1/v isotopes will be vastly higher than those measured for neutrons at thermal energies.

Lattice has estimated the ULM neutron capture fission cross-section to be more than 1 000 000 barns for U-235, and >50 000 barns for Pu-239, compared to ~582 barns for neutrons at thermal energies. By comparison, the stable isotope with the highest measured thermal neutron absorption cross section is gadolinium-157 at ~49 000 barns. Unstable Xe-135 (its half life is only ~ 9 hrs) has a measured thermal neutron capture cross-section of ~2.9 million barns. Given their unique absorptive properties, ULM neutrons could be used as extraordinarily effective tools for triggering fission in fissile isotopes and transmuting any isotopes that can capture extremely low-energy neutrons, i.e., follow the 1/v rule.

ULM NEUTRONS TRANSMUTE NUCLEAR WASTES

Weak interaction ULM neutrons have the potential to become a flexible technological tool that can be used to transmute one collection of target elements or isotopes into others; especially to clean-up radioactive wastes. For example, dangerous caesium, strontium, and technetium isotopes could be transmuted into stable elements [8] (see Chapter 32).

LENR-based nuclear waste remediation techniques would entail a multi-step process of transforming entire spent fuel rod assemblies into specific types of nano-particulate targets with high surface-to-volume ratios that would enable them to come into close contact with locally generated LENR ULM neutrons. In principle, it could be a straightforward process that is technologically feasible and possibly very cost-effective.

Importantly, some aspects of a future LENR-based nuclear waste remediation technology have already been explored in the laboratory. Specifically, in a long series of important experiments, Dr. Yasuhiro Iwamura and his colleagues at Mitsubishi Heavy Industries in Japan have clearly demonstrated the transmutation of caesium to praseodymium and strontium to molybdenum by LENR ULM neutron-catalyzed reactions [9], consistent with the Widom-Larsen theory [10].

Similarly, the characteristic LENR ULM neutron transmutation product mass spectrum is probably known. We believe it was first discovered experimentally back in the mid-1990s by both George Miley [11] in the US and Tadahiko Mizuno [12] in Japan. Instead of the two-peak fission product mass spectrum obtained from present-day nuclear reactors, it is a distinctive 5-peak mass spectrum that appeared in Miley's experimental data (see Chapter 32, Fig. 32.2).

Working 'backwards' from the experimentally measured product spectrum, Miley interpreted this transmutation data as being a supposedly 'slow' fission spectrum of hypothetical unstable "complex nuclei" with atomic masses A = ~40, 76, 194, and one superheavy at A ~310, that were produced during the LENR process.

In our opinion, Miley's interpretation of the above data was incorrect. On the contrary, according to the Widom-Larsen theory of LENRs, the data reflect a unique, characteristic signature of the absorption of large fluxes of ULM neutrons by atomic nuclei and related rapid beta decay processes. In that regard, we developed a simple 2-parameter optical model of ULM neutron absorption [13] that produces striking results when compared to Miley's data (see [7] and Chapter 32 for a simplified description of the model) .

The five peaks traced out by the solid line in Fig. 32.2 [13] represent the output of the simple 2-parameter optical model of ULM neutron absorption that is simply overlaid on top of the product mass spectrum observed in one of Miley's multiple LENR experiments. The five experimentally measured mass spectrum peaks in Miley's data line-up with the model's five calculated maximum resonance peaks for absorption of ULM neutrons as a function of atomic mass (A). The degree of correspondence is noteworthy.

Importantly, Miley and Mizuno's observed array of transmutation products did not contain any significant or detectible amounts of hot radioactive or fissile isotopes; nor hard gamma radiation and energetic neutrons. Such results are entirely consistent with the Widom-Larsen theory of LENRs [10]. This data also strongly suggest that absorption of large fluxes of LENR ULM neutrons by mixed isotopic systems likely produces very unstable, extremely neutron-rich intermediate nuclear reaction products that quickly transmute into stable isotopes via serial cascades of very rapid beta decays.

Consistent with Miley, Mizuno, and Iwamura et al's experimental data [9, 11, 12], the Widom-Larsen theory of LENRs [10] implies that if you 'cook' a collection of different elements/isotopes long enough with appropriately large fluxes of LENR ULM neutrons, the resulting transmutation product spectrum will eventually contain a complex array of almost entirely stable isotopes. Over long 'cooking times', benign transmutation products should be distributed across 5 characteristic mass-peak regions that would be very similar to what Miley and Mizuno discovered over a decade ago.

In the future, compact LENR ULM neutron generator systems could be developed and deployed for cost-effective on-site treatment of nuclear wastes presently stored in cooling ponds next to reactors that produced them. Spent fuel rod assemblies could be processed into particulates in on-site containment facilities and injected into co-located LENR transmutation reactors. These specialized reactors would then 'burn' hot radioactive wastes down to stable isotopes using large fluxes of ULM neutrons. If successfully developed, such a technology could significantly reduce nuclear waste remediation costs for decommissioning fission power plants, and significantly increasing their safety and profitability for those still operating.

Rather than just burning up spent fuel rod assemblies located at reactor sites or after removal of fissile isotopes at reprocessing facilities, excess heat generated during waste burn up with LENR ULM neutrons could be harvested with various types of power generation technologies to produce additional electricity that could either be utilized locally at a commercial power plant or connected and sold into the electricity grid.

Rather than just burning up spent fuel rod assemblies located at reactor sites or after removal of fissile isotopes at reprocessing facilities, excess heat generated during waste burn up with LENR ULM neutrons could be harvested with various types of power generation

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Independent Science Panel (ISP) (http://www.indsp.org), May 2003, consisting of dozens of scientists from many disciplines. Its highly influential report (The Case for a GM-Free Sustainable World) calling for a ban on GM crops and a comprehensive shift to sustainable agriculture was presented in the UK Parliament and European Parliament, circulated worldwide, and translated into 5 or more languages.

Sustainable World Global Initiative, launched on the web April 2005, http://www.i-sis.org.uk/SustainableWorldInitiativeF.php. First international conference, held 14/15 July 2005 in UK Parliament, followed by a weekend workshop 21 January 2006, out of which came a proposal for an innovative food and energy self-sufficient 'Dream Farm 2' for demonstration/education/research purposes, the definitive report, Food Futures Now (2008) shows how organic agriculture and localised food and energy systems can provide food and energy security and free us from fossil fuels. The present volume *Green Energies* sets the target for 100 percent renewables by 2050 and documents how all countries can achieve that with a combination of appropriate options.

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