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Emerging technologies and research for New Zealand's economic development and associated risk management

Literature Review

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1 *Executive summary*

This literature review examines emerging technologies and research that may offer significant economic opportunities in New Zealand industry sectors or introduce significant changes in risk management that may have implications for New Zealand in terms of improved management of environmental or health risks.

Six main areas of technology development are reviewed – biotechnology, nanotechnology, chemistry, information and communications technology, waste management, and clean energy. For each area, some significant recent trends and developments are highlighted. This approach demonstrates the diverse, diffuse and continuing nature of technology development, which precludes precise prediction of specific technologies that will most significantly affect economic opportunities and/or risk management in New Zealand. The review therefore focuses on illustrating general feature of technology development in each of these areas, so future identification of specific technologies of interest may be easier. For some of the technology areas, potential risks (that may be relevant from a regulatory perspective) are also highlighted.

International biotechnology developments are hugely relevant for New Zealand, both because of their inevitable impact on the international competitiveness of New Zealand's own biological industries (e.g. agriculture, food) and the domestic demand for new health and well-being technologies. Biotechnologies covered include selection and screening technologies (such as epigenetics and functional genomics), genetic modification (of plants and animals), xenotransplantation, and stem cell research.

Nanotechnology is a relatively new area of science but is progressing very rapidly. Potential applications in sustainable manufacturing, electronics, automotive, construction, health and life sciences, energy, and environmental management are covered. This section also looks at potential risks, with particular reference to the need for the sector itself to be alert to uncertainties that may impact on public health and environment risks. A key challenge for anticipating and managing emerging nanotechnologies is that such technologies are more likely to be embedded in other products and sectors, than to emerge within a discrete nanotechnology sector.

Similarly for chemistry and chemicals, emerging technologies are often not explicit, but are instead embedded in other sectors/industries. Notwithstanding the huge and ever expanding range of chemicals being developed and applied, much of recent research and technology development in chemistry/chemicals is aimed at improving the production efficiency and environmental quality of chemical processes. Some key areas illustrating this phenomenon included catalysis chemistry, 'green chemistry' and packaging chemicals. A key feature of this sector is the rapid growth of chemical industry in China (e.g. pesticides) that is in turn increasingly becoming the new source of many traditional classes of chemicals being traded internationally.

A section on information and communications technology is included, mainly to illustrate how technology development in a transformational area is continuing and in turn influencing technology development in many other areas (including those that are more immediately relevant to the current review). Key areas highlighted include developments in the internet and computing, along with implications for the economy, society and environment.

The development and application of waste management technologies are also reviewed. This section illustrates a key area of integration and application of various other technologies (in processes such as bioremediation and energy recovery), and is increasingly embedding very specialised biological and chemical technologies. On the other hand, this area highlights the importance of social technologies (e.g. life-cycle assessment) for identifying opportunities and priorities to change economic and social practices to enable better outcomes.

Recent trends and developments in energy technologies are reviewed also, highlighting the combination of highly specialised technologies (e.g. new solar energy systems based on chemistry and nanotechnology developments) and increasingly scale and efficiency in broad technology areas (e.g. increasing turbine size for wind energy).

The review highlights increasingly internationalised processes of research and technology development, as well as a hugely diverse range of possible technologies that may affect New Zealand more directly. A better understanding of these internationalised technology development processes (rather than a specific set of key technologies) should inform the future development of regulatory processes relevant to managing biological and chemical risks in New Zealand.

2 *Introduction*

Technological change is a constant for our society, bringing with it constant economic, environmental and social development opportunities as well as challenges to our social, ethical and regulatory norms and standards. In the 17th century for example, the development of blood transfusion technology in Europe (early experimentation for which included animal – human transfusions) was carried out in the absence of robust scientific standards, let alone ethical guidelines, but nevertheless seriously tested society's ethical tolerances at the time.

Three hundred and fifty years later, most people take this technology for granted but some communities – for economic reasons – still do not have routine access to it and still others shun it on moral grounds. And in the meantime other major technological changes have similarly been developed and become routine (e.g. motorised vehicular transport), while others (e.g. nuclear energy generation) have found limited favour.

Today, Governments around the world define policy and regulatory standards governing the development and deployment of new technologies. In this context, the Ministry for the Environment has sought a survey of emerging technologies, developments and research that have potentially significant implications for New Zealand in terms of either new economic opportunities or improved management of environmental and health risks. While the Ministry's immediate interest is with biological and chemical technologies, this review has taken a broader view, to include some significant technology areas that could influence developments in the biological and chemical areas.

Given the potentially wide scope of such a review, it makes practical sense to constrain it in terms of;

- Timeframe – likely to have an impact within the next 10-15 years;
- Technology areas – potential to have major disruptive or transformational impacts on industry and society;
- Sources – countries with relatively greater scale and pace of technological development.

It is also useful to consider prioritisation processes influencing science and technology investment in major countries, to steer a literature review towards major areas of technological change. For example, a survey of science and technology priorities in public research priorities in Europe, USA and Japan highlighted the following key fields[1];

- life sciences, genomics and biotechnology for health;
- nanotechnologies, knowledge-based multifunctional materials, new production processes;
- information society technologies;
- sustainable development, global change and ecosystem.

When surveying emerging technologies, developments and research, it is useful to consider different types of associated innovation, for example[2];

- Innovations within a system, that advance or accelerate the rate of development of a system – often seen as incremental change. In practice, most technological change observed over 5-15 year time-frames is of this type;
- Changes in paradigms – occasional transformational change through paradigm shifts. This can include changes external to the technology itself, such as changes in societal ethics, such as the emergence of an environmental ethic leading to a new economic-environmental paradigm;
- Interruption of a system – resulting from the collapse or destruction of critical system elements. This can occur, for example, where public or consumer reactions interrupt a technological pathway – such as the halting of GM crop trials due to a consumer backlash;
- Change in interdependencies – changes in the relationship between system elements. This can occur for example when new technologies allow a new development pathway for related technologies – such as testing pharmaceutical drugs through computer-based techniques rather than animal/human trials.

A literature review of emerging technologies, developments and research can be further focused by looking for key signals;

- Convergence of science disciplines (e.g. biotechnology, nanotechnology);
- Bottlenecks – rate-limiting steps that, when overcome, can be associated with technical breakthroughs;

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[1] European Union, 2006. Emerging science and technology priorities in public research policies in the EU, US and Japan. 116pp. ISBN 92-79-01674-1.

[2] Futurewatch: Biotechnologies to 2025. Ministry of Research, Science and Technology (2005). 128pp.

- Uncertainties – reflecting cross-roads for different future paths; and
- Anomalies – unusual things that don't fit the pattern.

This review has been conducted with reference to such constraints and parameters. It is not exhaustive, nor does it purport to be predictive. Rather, it highlights significant technologies, developments and research for which there is a significant likelihood of new economic opportunities in key economic sectors for New Zealand or improved management of environmental and health risks.

The time-frame constraint has been particularly important for this review. Technologies and research likely to have a significant impact within 10-15 years are likely to be already well beyond initial discovery stages and on the path of development and deployment. This time-frame constraint also increases the focus on incremental change within existing technological systems, with less frequent incidences of paradigm shifts, system interruptions or interdependency changes.

The industry-sector constraint has also been important, providing a clear frame or reference within which to assess the significance of emerging technologies and research in otherwise broad areas. The review has been structured around key areas of technology development, within which sector-based approaches and applications are outlined. The resulting matrix of technology and sector perspectives should enable key technological developments to be distilled in a practical way.

This literature review provides the basis for modelling potential economic impacts of some emerging technologies. Any such modelling will always be constrained by the lack of firm evidence of likely economic "shocks" resulting from adoption and use of the new technology. While a literature review may indicate possible rates and scale of impact, it is likely to be just as important (if not more so) for highlighting and characterising key aspects of research, technology development and innovation processes.

3 Biotechnology

For millennia, people have carried out research and developed new technologies to alter the nature, pace and scale of natural biological processes, in order to improve agriculture, medicine, manufacturing and various other economic and social areas. Public responses to biotechnologies have differed strongly between different countries and cultures. Stem cell research, for example, is widely accepted in the UK but has been controversial in the US. It is the other way around for genetically modified crops.

Biotechnology is particularly significant for New Zealand industry, given the strong contribution biological industries make to our economy and their strong interaction with our environment, as well as obvious links to human health and well-being. About $^2/_3$ of New Zealand's export earnings are derived from biological industries, spanning agriculture, horticulture, human and animal health, and other natural products[3].

The range of technological developments in the overall field of biotechnology is immense and daunting, so a judicious selection needed to be made for this literature review. This section accordingly focuses on selection and screening technologies, genetic modification, xenotransplantation, stem cell research, and human genetic testing.

Selection and Screening Technologies

In recent years, there has been a steady stream of scientifically significant but publicly unremarkable biotechnology developments in the general areas of screening and selection. Technologies are being developed and applied to improve understanding of the genetic basis of different traits – in plants, animals and humans. This in turn is enabling more active screening and selection. Some examples of such technologies are outlined in this section.

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[3] http://www.maf.govt.nz/agriculture/statistics-forecasting/international-trade.aspx

Functional Genomics

The completion of a high-quality, comprehensive sequence of the human genome in 2003 firmly established the genomic era of research[4]. It has paved the way for new and expanding fields of research in areas like elucidating the structure and function of genes, and translating genome-based knowledge into health benefits. At the same time, attention is also being paid to promoting the use of genomics to maximise benefits and minimise harms.

The field of functional genomics attempts to make use of the vast wealth of data produced by genomic projects to describe gene (and protein) functions and interactions. The goal of functional genomics is to understand the relationship between an organism's genome and its phenotype. This in turn is used to attempt answer questions about the function of DNA at the levels of genes, RNA transcripts and protein products. Functional genomics involves studies of natural variation in genes, RNA and proteins over time (such as during an organism's development) or space (such as its body or regions), as well as studies of natural or experimental functional disruptions affecting genes, chromosomes, RNA or proteins.

Functional genomics has the potential to expand and synthesise genomic and proteomic function into an understanding of the dynamic properties of an organism at cellular and/or organism levels. This would provide a more complete picture of how biological function arises from the information encoded in an organism's genome. This could, for example, help scientists find a treatment or cure for a particular human disease, based on an understanding of how a particular mutation leads to a given phenotype.

Proteomics

Proteomics is the large-scale study of proteins, and is considered the next step in the study of biological systems. It is much more complicated than genomics mostly because while an organism's genome is more or less constant, the proteome differs from cell to cell and from time to time.

One of the most promising developments emerging form proteomics has been the identification of potential new drugs for treating diseases. This relies on genome and proteome information to identify proteins associated with a disease, which computer software can then use as targets for new drugs. If a certain protein is implicated in a disease, its 3-D structure provides the information to design drugs to interfere with the action of the protein[5].

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[4] Collins, F.S., Green, E.D., Guttmacher, A.E. and Guyer, M.S. 2003. A vision for the future of genomics research. Nature 422: 835-847.

[5] Wang, J. 2009. Chemical proteomics: a powerful tool for protein biology and drug discovery. Discovery Medicine 2: 22.

Epigenetics

Epigenetics is the study of how individual genes and components of individual genes develop and change over time in response to environmental conditions or other factors without changing the basic DNA sequences[6]. An example of this phenomenon is the link between a mother's diet during pregnancy and the risk of obesity in subsequent generations[7].

The field of epigenetics has grown swiftly over recent years, due to the recent shift in major life science research from genome sequencing to the understanding of the mechanism and regulation of genomes. Some key areas illustrating the rapid development of this field include;

- Onset of cancer – in particular, gastric cancer is believed to be closely related to epigenetics (due to the apparent bacterial infection inducing epigenetic mutations)[8];
- Neuropsychiatric and neurodevelopmental disorders – evidence is emerging that links the incidence of some depression and bipolar disorders to epigenetic changes, but this research is still heavily based on estimation and the involvement of epigenetics is still to be clarified[9]; and
- Regulation of milk production in dairy cows – apparently explaining a substantial proportion of phenotypic variation in milk production in the dairy cow[10].

Genetic Modification

Genetic modification alters the genetic makeup of an organism using techniques that introduce heritable material from outside the host organism. Where that genetic material comes from another species, the resulting organism is called transgenic,

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[6] Berger, S.L., Kouzarides, T., Shiekhattar, R., Shilatifard, A. 2009. An operational definition of epigenetics. Genes and Development 23: 781-783.

[7] Godfrey, K.M., Sheppard, A., Gluckman, P.D., Lillycrop, K.A., Burdge, G.C., McLean, C., Rodford, J., Slater-Jeffries, J.L., Garratt, E., Crozier, S.R., Emerald, B.S., Gale, C.R., Inskip, H.M., Cooper, C. and Hanson, M.A. 2011. Epigenetic gene promoter methylation at birth is associated with child's later adiposity. Diabetes 2011, Apr. 6.

[8] Enomoto, S., Ando, T. and Ushijima, T. 2008. Aberrant DNA methylation induced by *Helicobactor pylori* in gastric carcinogenesiss," Japanese Journal of Clinical Medicine 5: 89-94.

[9] Kato, T. 2008. Epigenetics of mood disorder. Japanese Journal of Molecular Psychiatry 8: 38- 44.

[10] Singh. K., Erdman, R.A., Swanson, K.M., Molenaar, A.J., Maqbool, N.J., Wheeler, T.T., Arias, J.A., Quinn-Walsh, E.C. and Stelwagen, K. 2010. Epigenetic regulation of milk production in dairy cows. Journal of Mammary Gland Biology and Neoplasia 15: 101-112.

whereas if it comes form the same species it is called cisgenic. Genetic modification can also be used to remove genetic material, creating a knock-out organism.

More recently, new genetic modification technologies have offered vast shifts in the scale and pace of such research and technological development, while at the same time challenging different social and ethical tolerances. It is very likely that the science and opportunities genetic modification provides will continue to advance at a pace that is hard for others in society to keep up with.

Genetic modification processes include:

- Isolating the gene – typically by multiplying the gene using polymerase chain reaction (PCR), and enabling the organism's genome to be studied, sequenced and/or copied. Once isolated, the gene maybe inserted into a bacterial plasmid;
- Constructs – typically made using recombinant DNA techniques, to combine the gene to be inserted with other genetic elements in order for it to work properly. Most constructs contain a promoter and terminator region as well as a selectable marker gene, so the location and level of gene expression can be controlled;
- Gene targeting – allowing new genetic material to be inserted at a specific location in the host genome or to generate mutations at desired genomic loci. This involves homologous recombination to target desired changes, but tends to occur at low frequencies in plants and animals so requires the use of selectable markers;
- Transformation – DNA is typically inserted into plants using Agrobacterium-mediated recombination, and into animals through microinjection through the cell's nuclear envelope or through the use of viral vectors. Biolistic techniques involve shooting particles of gold or tungsten with DNA into young plant cells or plant embryos;
- Selection – screening, using selectable markers, those cells that have been successfully transformed with new genetic material;
- Regeneration – regrowing organisms from cells transformed with new genetic material. In plants, successful transformation results in the transgene existing in every cell, while in animals the inserted DNA must be present in the embryonic stem cells; and
- Confirmation – further tests using techniques such as PCR or bioassays are needed to confirm that the gene is expressed and functions correctly.

Genetically modified crops

One of the best-known and controversial applications of genetic modification is the creation of genetically modified food. Genetically modified crops are being applied increasingly in agriculture systems around the world:

- First-generation crops provide easier crop management and/or increased yield through pest and disease protection or resistance, and/or herbicide resistance[11]. There are also fungal and virus resistant crops developed or in development[12]. Reduced chemical use in turn can decrease the severity and frequency of damages caused by chemical pollution[13]. A recent global review of the application of such technologies concluded that insect-resistant and herbicide-tolerant crops are beneficial to farmers and consumers, producing large aggregate welfare gains as well as positive effects for the environment and human health[14];
- Second-generation crops being developed aim to improve yield by improving salt, cold or drought tolerance[15], and to increase the nutritional value[16]; and
- Third generation crops (mostly in early stages of development) consist of "pharmaceutical crops", containing edible vaccines and other drugs (e.g. lactoferrin and lysosyme in rice[17]). Although no drugs from pharmaceutical crops are currently on the market, open field trials of such crops began in the United States in 1992 and have taken place every year since.

The United States accounts for more than 50% of the total area planted globally in genetically modified crops, with about 50 million hectares of mainly soybean, maize, cotton and canola[18]. These crops generally contribute ingredients for processed foods. About 10 years ago, introduction of transgenic fresh produce appeared imminent, with limited amounts of sweet corn and squash being retailed. However, the withdrawal from market of the Flavr-Savr® tomato and Starlink® feed corn, a

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[11] Magaña-Gómez JA, de la Barca AM (2009). "Risk assessment of genetically modified crops for nutrition and health". *Nutr. Rev.* **67** (1): 1–16.

[12] Islam, A. 2006. Fungus resistant transgenic plants: strategies, progress and lessons learnt. Plant Tissue Culture and Biotechnology 16: 117-138.

[13] http://www.agbioworld.org/pdf/raney.pdf

[14] http://www.europabio.org/positions/GBE/PP+080110-Socio-economic-impacts-of-GM-Crops-GMO.pdf

[15] http://www.adelaide.edu.au/news/news34361.html

[16] http://www.betterhealth.vic.gov.au/bhcv2/bhcarticles.nsf/pages/genetically_modified_foods?open

[17] http://www.ventria.com/

[18] http://www.attra.org/attra-pub/geneticeng.html

clear divergence between developmental pathways for processed and fresh foods has occurred in the US. While field trials are being carried out on a wide range of fresh foods (e.g. cabbage, sweet corn, cucumber, lettuce, eggplant, applies, cherries, grapefruit), the path to market appears to be much slower and more cautious than for processed foods.

Genetically modified animals

Genetic modification of agricultural animals is generally being developed for six main purposes:

- Scientific and medical research – especially with mice, to study how animals function and to help understand and develop treatments for both human and animal diseases;
- Improving human health through production of novel replacement proteins, drugs, vaccines and tissues for the treatment and prevention of human disease (e.g. for cystic fibrosis) – typically by transferring genes coded for such proteins into sheep or cattle enabling these proteins to be produced in milk) or to provide organs for transplant to humans (by altering the immune system of the animals so the organs "appear" to be of human origin);
- Improving animal food production traits to help meet global demand for more efficient, higher quality and lower-cost sources of food (e.g. strains that grow faster, shower greater disease resistance);
- Contributing to improving the environment and human health with the consumption of fewer resources and the production of less waste;
- Enhancing health well-being and welfare of farm animals; and
- Producing high-value industrial products.

The reality of genetically modified animals began with "Dolly" the sheep, created by Scottish scientist Ian Wilmutt in 1996[19], using a cloning technique called nuclear transfer. Dolly went on to reproduce on several occasions. However, her premature death in 2003 fuelled ethical concerns about mammalian cloning.

Some novel transgenic animal applications currently being developed include;

- Transgenic chickens producing concentrated amounts of protein drugs in their egg-whites[20];

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[19] Campbell, K. H. S., McWhir, J., Ritchie, W. A. & Wilmut, I. 1996. Sheep cloned by nuclear transfer from a cultured cell line. Nature 380: 64-66.

[20] http://www.technologyreview.com/biotech/18078/?a=f

- Transgenic goats producing spider silk protein (for high-value industrial applications) in their milk[21];
- Genetic modification of pigs for xenotransplantation[22]; and
- Transgenic cattle producing human lactoferrin in their milk for the treatment of inflammatory bowel diseases[23].

AgResearch (one of New Zealand's CRIs) is a world-leader in transgenic animal research. Their projects have included developing new hormones, vaccines and diagnostic products for sheep, transgenic producing higher levels of casein or milk proteins as potential treatments for multiple sclerosis[24].

Research on genetic modification of animals is generally heavily regulated in most "Western" countries – but less so in places like China and Brazil. A recent report has indicated that scientists there have successfully introduced human genes into 300 dairy cows to produce milk with the same properties as human breast milk, in particular containing the human proteins lysosyme and lactoferrin[25]. The scientists behind this research believe milk from herds of genetically modified cows could provide an alternative to human breast milk and formula milk for babies. Their research appears to have commercial backing.

China's animal biotechnology research is mostly still at "discovery" stage (in universities), but some private sector companies (such as Genon Shanghai) are also active. Significant areas of development include research with cattle, pigs, goats, chickens and rabbits[26]. As science capability and investment expand in countries with typically lower levels of regulation (e.g. China, Brazil), scientific advances and associated economic opportunities may proceed more rapidly away from those countries with strict controls.

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[21] Jones, J., Rothfuss, H., Steinkraus, H. and Lewis, R. 2010. Transgenic goats producing spider silk protein in their milk; behavior, protein purification and obstacles. Transgenic goats producing spider silk protein in their milk; behavior, protein purification and obstacles. Transgenic Research 19: 135.

[22] Keßler, B., Kurome, M., Klymiuk, N., Wünsch, A., Seissler, J. and Wolf, E. 2011. New transgenic pigs for xenotransplantation, part 2: strategies to overcome cellular rejection. Xenotransplantation 18: 65.

[23] Hyvönen, P., Suojala, L., Haaranen, J., von Wright, A. and Pyörälä, S. 2006. Human and bovine lactoferrins in the milk of recombinant human lactoferrin-transgenic dairy cows during lactation. Biotechnology Journal 1: 410-412.

[24] http://www.ermanz.govt.nz/Documents/GMF98009-and-GMD02028-annual-report-2010.pdf

[25] http://www.telegraph.co.uk/earth/agriculture/geneticmodification/8423536/Genetically-modified-cows-produce-human-milk.html

[26] USDA Foreign Agricultural Service, 2009: China moves forward in new technologies. GAIN Report CH9138.

Climate Change Mitigation

Biotechnology is offering significant opportunities for mitigating climate change. Some key areas of research and technology development are outlined in this section.

Reducing fertiliser and other inputs associated with climate change

There is growing interest in the potential of genetically modified crops to reduce the scale of greenhouse gas emissions from agricultural production. In particular, reducing fertiliser use (especially nitrogen) may be possible through the insertion of a gene for the alanine aminotransferase enzyme that boosts the ability of a wide variety of plants to take up nitrogen from the soil[27]. Reduced fertiliser use should in turn reduce emissions of nitrous oxide. It has been estimated that cutting fertiliser use by a third would reduce greenhouse gas emissions by more than grounding every single aircraft in the world[28]!

Genetically modified crops are already contributing to reducing CO_2 emissions in two main ways[29]:

- Permanent savings in CO_2 emissions through reduced use of fossil-based fuels, associated with fewer pesticide/herbicide applications; and
- Additional savings from conservation tillage (through precluding the need for ploughing cropped land), leading to additional soil carbon sequestration.

CO_2 sequestration during photosynthesis

Recent discovery of a more efficient variant of RuBisCo (the key enzyme involved in CO_2 sequestration during photosynthesis) paves the way for increasing the photosynthetic efficiency of crop and forest plants[30]. The RuBisCo variants that evolved through three rounds of random mutagenesis and selection exhibited 5-fold improvement in specific activity relative to the wild-type enzyme. Such large changes in RuBisCo efficiency could potentially lead to faster plant growth, quicker sequestration of CO_2 from the air and more efficient plant removal of greenhouse gases from the atmosphere.

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[27] http://www.arcadiabio.com/nitrogen

[28] Aldhouse, P. 2008. New generation of GM crops could reduce greenhouse gas emissions by more than grounding all the aircraft in the world. New Scientist.

[29] Brookes, G. and Barfoot, P. 2009. Global impact of biotech crops: socio-economic and environmental effects 1996-2007. PG Economics Ltd.

[30] Parikh, M.R., Greene, D.H., Woods, K.K. and Matsumara, I. 2006. Directed evolution of RuBisCO hypermorphs through genetic selection in engineered E.coli . Protein Engineering, Design & Selection 19: 113-119.

Reducing ruminant greenhouse gas emissions

Various lines of enquiry are underway internationally to find ways to reduce the emission of methane by ruminant animals. One approach is to shut down methanogens – the enzymes that produce methane, using genomic information to design inhibitory compounds. Another approach is to promote acetogenesis, a pathway that converts CO_2 and H_2 into acetate (as an alternative to the methane-producing pathway)[31]. Such lines of research are likely to open up opportunities for genetically modified pastures and/or animals.

Scientists at Gramina, a joint biotechnology venture by PGG Wrightson Genomics and Australia's Molecular Plant Breeding Cooperative Research Centre are developing a grass that will cut the amount of methane cows burp – and which will grow in the hotter climates expected with climate change[32]. AgResearch is developing a high-lipid grass that could enable high animal productivity with low methane emissions[33].

New Zealand is (and needs to be) at the forefront of international research on reducing methane emissions, in line with the significant contribution ruminant animal industries make to our national economy. The recently opened New Zealand Agriculture Greenhouse Research Centre is therefore likely to be a significant source of new knowledge and technology in this area.

Xenotransplantation

Xenotransplantation involves transplanting organs from one species to another. Although xenotransplantation is not new, scientists have only recently begun to solve immunological problems such as transplant rejection. Some experts now believe organ transplantation may be able to solve the otherwise major problem of organ shortage[34].

Currently most international research is centred on the suppression of rejection and infection cause by animal organs. There is also a large focus on gene splicing and cloning of pigs to aide in the success of this therapy (this would help perfect

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[31] Clark, H., Kelliher, F. and Pinares-Patino, C. 2011. Reducing CH4 Emissions from Grazing Ruminants in New Zealand: Challenges and Opportunities. Asian-Australian Journal of Animal Science 24: 295-302.

[32] http://www.seedquest.com/News/releases/2008/may/22494.htm

[33] http://www.nzherald.co.nz/science/news/article.cfm?c_id=82&objectid=10607618

[34] Murray, B. 2001. Making a pig of yourself: the promise and problems of xenotransplantation. FACSNET, Apr. 3 2001, http://www.facsnet.org/tools/sci_tech/biotek/pig.php3

xenotransplantation by preventing rejection and infection and lower the amount of immunosuppressive drugs required)[35].

The New Zealand company *Living Cell Technologies* is at the forefront of international application of xenotransplantation technology. It is the first company globally to enter clinical trials using therapeutic porcine cell implants[36]. Its lead product Diabecell® provides a therapy for people with unstable Type 1 diabetes.

Stem Cell Research

Stem cells are biological cells found that can divide and differentiate into specialised cell types (and renew to produce more stem cells). The main clinical application of stem cells is a source of donor cells to be used to replace cells in transplantation therapy. In mammals, there are two broad types of stem cells – embryonic stem cells and adult stem cells. In a developing embryo, stem cells can differentiate into all the specialised cells of the body, but also maintain the normal turnover of regenerative organs, such as blood, skin or intestinal tissues. In adults, stem cells act as a repair mechanism for the body.

Embryonic stem cells

Embryonic stem cells are theoretically a potential source for regenerative medicine and tissue replacement after injury or disease. Nearly all research to date with embryonic stem cells has involved mouse embryonic stem cells or human embryonic stem cells. Stems cells can be sourced from spare embryos (e.g. "left-over" embryos stored at fertility clinics) or special purpose embryos (created in the lab for the sole purpose of extracting stem cells).

There are currently no approved treatments using embryonic stem cells. The first human trial was approved (by the US Food & Drug Administration) in January 2009[37]. The first human medical trial started in the USA in October 2010, for spinal injury victims[38]. Many countries currently have moratoria in place for either embryonic stem cell research or the production of embryonic stem cell lines.

Stem cells can now be artificially grown and transformed, through cell culture, into specialised cell types consistent with various tissues such as muscles or nerves.

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[35] http://www.eurotransplant.org/?id=xeno

[36] http://www.lctglobal.com/

[37] Winslow, R. 2009. First Embryonic Stem-Cell Trial Gets Approval from the FDA. The Wall Street Journal. 23 January 2009.

[38] http://geron.com/investors/factsheet/pressview.aspx?id=1235

Adult stem cells

Most adult stem cells are "lineage restricted" – i.e. can only divide to form cells consistent with the tissue or organ from which they originated – and are therefore referred to by their tissue origin. Adult stem cells able to divide into different specialised cell types are rare and generally small in number, but can be found in a number of tissues including umbilical cord blood. Much adult stem cell research has focused on clarifying their capacity to divide or self-renew indefinitely and their differentiation potential[39].

Adult stem cell treatments have been successfully used for many years to treat leukaemia and related blood/bone cancers through bone marrow transplants. Adult stem cells are also used in veterinary medicine to treat tendon and ligament injuries in horses.

Research evidence has emerged recently demonstrating the ability to convert virtually any cell type in the body into a cell almost identify to embryonic stem cells. Following seminal work in 2006[40], there has been a flurry of activity signalling rapid development of a technology with the potential to avoid ethical and moral issues in delivering many of the potential health benefits of embryonic stem cells.

Application

Medical researchers believe that stem cell therapy has the potential to dramatically change the treatment of human disease – in areas like cancer, Parkinson's disease, spinal cord injuries, multiple sclerosis and muscle damage[41],[42]. Market analysts are predicting compound annual growth rates of 30% in the market for stem cells in regenerative medicine and 44% in the market for human adult stem cells for cell-based therapeutics[43].

Likely developments over the next 10-15 years are illustrated by the intentions of pharmaceutical and health care companies. GSK, for example, is using two distinct

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[39] Gardner RL (2002). Stem cells: potency, plasticity and public perception. Journal of Anatomy 200: 277–82.

[40] Takahashi, K. and Yamanaka, S. 2006. Induction of pluripotent stem cells from mouse embryonic and adult fibroplast cultures by defined factors. Cell 126: 663-676.

[41] Lindvall O (2003). "Stem cells for cell therapy in Parkinson's disease". Pharmacol Res 47 (4): 279–87.

[42] Goldman S, Windrem M (2006). Cell replacement therapy in neurological disease. Philosophical Transactions of the Royal Society of London B Biological Science 361: 1463-1475.

[43] http://www.bccresearch.com/report/stem-cell-technology-future-bio035c.html

scientific approaches to develop new medicines using adult and embryonic stem cells[44];

- Regenerative therapeutics – identifying medicines that active stem cells in patients and regenerate cells lost in the disease process (e.g. pancreas cells in diabetes or brain cells in Parkinson's disease. GSK's first regenerative medicine (Promacta™ – a bone marrow stem cell activating drug) was approved in 2008 for testing in patients);
- Cellular tools – using stem cells to generate a range of cell types (many of which cannot be safely or physically collected from patients) to determine drug activity and toxicity, e.g. liver hepatocytes, brain neurons or culture of contracting heart cells.

In collaboration with other health research entities, GSK is also working on stem cell therapies to treat rare genetic disorders.

Human Genetic Testing

Testing (or screening) for known genetic traits or conditions (e.g. colour blindness) has been used for many years. New technologies building on the knowledge base generated by the human genome project are making it possible to test for a wider range of disorders in larger numbers of people more rapidly and at lower cost.

While an increasing array of genetic tests are available to clinicians, medical professionals are often concerned about using such tests in the absence of robust data about appropriate use of test results in patient management[45]. Uncertainties are particularly high for tests that identify genetic susceptibility to common diseases (e.g. diabetes, coronary heart disease). Major types of genetic testing that are becoming increasingly available include:

- Genetic diagnostic tests – diagnosing genetic disorders using clinical criteria;
- Gene expression profiling – measuring gene expression in specific disease states;
- Pharmacogenomics – test for gene variants associated with drug response; and
- Genetic susceptibility testing and personal genomics – identifying genes or gene variants potentially associated with a higher risk of a given disease.

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[44] http://www.gsk.com/policies/GSK-on-cloning-technologies-and-stem-cell-research.pdf

[45] Laberge, A and Burke, W. 2011. Clinical and public health implications of emerging genetic technologies. Seminars in Nephrology 30: 185-194.

While it is becoming increasingly possible to identify high-risk individuals and concentrate preventative measures on them, perhaps the main value of this work in the foreseeable future will be to provide a better understanding of the mechanisms of such disorders.

Risk Considerations

Genetic modification

Widespread safety, ethical and environmental concerns have been raised around the use of genetically modified food[46]. A major safety concern relates to human health implications, particularly whether toxic or allergic reactions could occur[47], although considerable testing and scrutiny is largely demonstrating product safety before products reach consumer markets[48]. Nonetheless, substantial consumer concerns continue to be expressed[49]. Ethical issues, reviewed soundly as long ago as 1999[50], include intrinsic concerns about "messing" with nature, as well as more contemporary concerns about corporate control of the food supply, intellectual property rights and the level of labelling needed. Environmental concerns include gene flow into related non-transgenic crops[51], "off-target" effects on beneficial organisms and impacts on biodiversity[52].

Not surprisingly, ethical and safety concerns are expressed even more strongly for genetically modified animals than for genetically modified plants. In addition to moral concerns about interfering with nature, additional concerns about welfare of genetically modified animals are expressed.

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[46] http://www.nch.go.jp/imal/Ethical_Com/Nuffield_Council/gm_crops_summary.pdf

[47] Malarkey, T. 2003. Human health concerns with GM crops. Mutation Research 544: 217-221.

[48] Key, S., Ma, J.K. and Drake, P.M. 2008. Genetically modified plants and human health. Journal of the Royal Society of Medicine 101: 290–298.

[49] Stone, R. 2011. Activists go on warpath against transgenic crops – and scientists. Science 25: 1000-1001.

[50] Robinson, J. 1999. Ethics and transgenic crops: a review. Electronic Journal of Biotechnology vol 2, issue 2.

[51] Lu, Bao-Rong, 2008. Transgene escape from GM crops and potential biosafety consequences: an environmental perspective. Collection of Biosafety Reviews 4: 66-141.

[52] John Innes Centre 2011. Impact of growing GM crops on biodiversity. http://www.jic.ac.uk/corporate/about/publications/gm-debate/gm-impact-on-biodiversity.htm

Xenotransplantation

The process is controversial for obvious reasons. Many people argue that research on this project should be continued because it has the potential to save millions of lives and cure multiple medical problems, but others think that research in this field should end immediately because of the people and animals that might suffer in order to perfect the therapy.

Stem cell research

There is still a lot of social and scientific uncertainty about stem cell research. One key technical concern is that transplanted stem cells could form tumours and become cancerous if cell division continues uncontrollably.

Research with human embryonic stem cells remains very controversial. Opponents hold that human life begins as soon as an egg is fertilised, and therefore consider any research that necessitates the destruction of a human embryo to be morally abhorrent. Proponents meanwhile point out that in the natural reproductive process, human eggs are often fertilised but fail to implant in the uterus, so a human egg with the potential for human life cannot be considered equivalent to a human being until it has at least been successfully implanted in the uterus[53].

The use of adult stem cells in research and therapy is not as controversial as for embryonic stem cells (because the production of adult stem cells does not require the destruction of an embryo). Strong legislative guidance is common in many countries, and there is much scope for more public discourse about the potential, technical risks and ethical issues associated with this area of science.

Human genetic testing

There is much public debate about how genetic testing might be further developed and applied. A recent article typical of this debate[54] highlighted major issues in this debate, referring to a study by a direct-to-consumer genetic testing company – *23andMe*. This personal genomics company has published its first genome-wide association study in an on-line journal, in which they identified genetic correlations for a variety of simple traits (e.g. freckles, photic sneeze reflex and asparagus anosmia) from data provided voluntarily by 10,000 users. While such large genetic datasets have the potential to reveal powerful knowledge about public and personal health, there is serious concern about how private companies will generate revenue from such data and whether governments will seek access to such data in the case of public health, public safety or national security emergencies.

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[53] http://www.aaas.org/spp/cstc/briefs/stemcells/

[54] http://www.scienceprogress.org/2010/07/defining-the-boundaries-of-genetic-testing/

In this rapidly developing field of scientific, medical and commercial endeavour, consumers of personal genomic tests are being encouraged to ensure researchers are more transparent about:

- conclusions reached from analysing genetic data;
- potential health benefits or risks to the consumer;
- possibilities of new cures or treatments that arise from analysing one's data; and
- protocols surrounding the transfer of data to third parties.

Overall, the enormous potential of human genetic testing (personal genomics) needs to be carefully developed with due regard given to information privacy, scientific validity and medical utility.

4 *Nanotechnology*

Nanotechnology (including nanoscience) is the study of manipulating matter on the nanoscale – 1 to 100 nanometres (m x $10^{-12)}$, and the novel properties that emerge at this scale. It usually involves developing materials or devices possessing at least one dimension within that size. Nanotechnology is very diverse, including developing new materials with nanoscale dimensions, or investigating whether we can directly control matter on the atomic scale.

Nanotechnology is neither a sector in itself, nor an industry. Rather, it is a general purpose toolkit contributing to product innovations in virtually all kinds of manufactured goods. It provides new understanding of atomic and molecular properties and processes that are predicted to lead to transformational developments across a range of sectors or industries. Impacts tend though to be broad, rather than deep, as the "nano-advantage" is often embedded at an early stage of the value chain (e.g. raw nano-materials), where it can remain largely invisible to the end-user.

Future prospects for nanotechnology appear highly positive – possibly following a trajectory similar to that for the world-wide web. Initial adoption occurred in the period 2004-2007, with the emergence of a variety of materials and products. While there were occasional business successes during this period, there were also many notable failures. Since 2008, nanostructured materials and nanoparticles have been incorporated into a growing range of products and processes, but usually in a low-key way. Technological and commercial progress over the last few years has been restrained in the wake of the global financial crisis.

Nanotechnology can be viewed as coming to the end of the first major development phase ("NT 1.0)". Over coming years, the emergence of "NT 2.0" will see continued demand for energy saving, resource conservation and environmental protection are likely to promote an explosive spread of applications and deeper penetration of nanotechnolgies in various application areas[55]. Industry commentators predict that the greatest commercial potential will lie in the manufacture of intermediates, because a high level of know-how will be needed to fit basic materials to particular end-user requirements (e.g. functionalised nanoparticles for medicine).

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[55] ftp://ftp.cordis.europa.eu/pub/nanotechnology/docs/enf2009_conclusions_en.pdf

Convergence of nanotechnologies with other fields, such as biotechnology and ICT, will also be significant. While nanotechnology offers considerable promise in areas ranging from medicine, electronics, biomaterials and energy production, there are also concerns about toxicity, environmental impacts of nanomaterials[56], and potential effects on global economics.

Current Science

The United States is setting the pace for nanotechnology innovation worldwide. A coordinated R&D approach is being facilitated through the National Nanotechnology Initiative[57], involving 25 Federal agencies with a range of research and regulatory roles and responsibilities. Areas of R&D being pursued include;

- Discovery and development of fundamental knowledge relating to nanoscale structures, processes and mechanisms;
- Discovery and understanding of novel nanoscale and nanostructured materials, leading to the ability to design and synthesise nanostructured materials with targeted properties;
- Applying principles of nanoscale science and engineering to create novel, or to improve existing devices and systems;
- Developing tools needed to advance nanotechnology research and commercialisation (e.g. instrumentation, standards);
- Enabling scaled-up, reliable and cost-effective manufacturing of nanoscale materials, structures, devices and systems;
- Establishing user facilities, major instrumentation and other activities that underpin national infrastructure for nanoscale science and technology;
- Understanding environmental health and safety impacts of nanotechnology development and corresponding risk assessment, risk management and risk mitigation; and
- Identifying broad implications of nanotechnology for society.

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[56] Buzea, C., Pacheco, I. and Robbie, K. 2007. Nanomaterials and nanoparticles: sources and toxicity. Biointerphases 2: MR17.

[57] http://www.nano.gov/about-nni

Applications

An on-line resource for listing manufacturer-identified nanotechnology products shows about 3-4 hitting the market every week[58]. Most applications are limited to the use of "first generation" passive nanomaterials (e.g. titanium dioxide in sunscreen, cosmetics and some food products; silver in food packaging, clothing, disinfectants and household appliances)[59]. Impacts of such applications on our business and our daily lives are generally developing only slowly. A comprehensive review[60] has concluded that much of what is sold as "nanotechnology" is in fact a recasting of straight-forward materials science.

Some key sector-based applications of nanotechnology over the next 10-15 years are outlined below.

Sustainable manufacturing

The very high surface:volume ratio (i.e. specific surface area) of nano-particles makes catalysis (and therefore reduced energy and material use) one of the principal ways nanotechnology is likely to contribute to sustainable manufacturing. In chemicals production, for example, 80% of the manufacturing processes involve at least one catalyst-promoted reaction. Recent developments include;

- the use of superparamagnetic metal oxide nanoparticles which act simultaneously as catalysts and an energy source for chemical synthesis in microreactors[61];
- photocatalytic materials in the construction and environmental sectors, such as the use of a TiO_2 "self-cleaning" layer on window glass[62]; and
- incorporating nanolayer coatings and nanoparticle fillers to lift the electrical, magnetic and optical behaviour of composite materials[63].

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[58] Project on Emerging Nanotechnologies. (2008) - http://www.nanotechproject.org/inventories/consumer/analysis_draft/

[59] http://www.americanelements.com/nanotech.htm

[60] Berube, DM 2005. Nanohype: The Truth Behind The Nanotechnology Buzz. Prometheus Books, 521 pp.

[61] Ceylan, S., Friese, C., Lammel, C., Mazac, K., and Kirschning, A. 2008. Inductive heating for organic synthesis by using functionalized magnetic nanoparticles inside microreactors. Angewandte Chemie 47: 8950-8953.

[62] http://www.titaniumart.com/photocatalysis-ti02.html

[63] Friedman, H., Eidelman, O., Feldman, Y., Moshkovich, A., Perfiliev, V., Rapoport, L., Cohen, H., Yoffe, A. and Tenne, R. 2007. Fabrication of self-lubricating cobalt coatings on metal surfaces. Nanotechnology 18: 115703.

Electronics

Nanotechnology offers massive opportunities for rogressive down-scaling of semiconductor devices, making equipment smaller, cheaper and less energy-consuming, particularly through nanoscale manufacturing processes. But with increasing size comes increasing complexity. For example, a 32 Gb flash memory contains about 30 billion transistors, each measuring just 40 nm (smaller than the common cold virus). Carbon nanotubes show great promise for other electronic applications[64], although more work is needed to refine their manufacturing.

Automotive

Nanotechnology could reduce the weight of many automotive components. A modern car contains 80-100 sensors and 50-80 processors and is as much as 30% heavier than its 1980s equivalent. Nanotechnologies could be applied in tyres, the power-train and control systems, structural components and exterior finishes. Early examples include economical and space-saving LED lighting, pollution-reducing catalytic converters and particle filters, and anti-friction coatings for engine components. Further development of nanocomposites will bring smart materials simultaneously optimising weight reduction, mechanical and thermal properties.

Construction

The construction industry is starting to be influenced by nanotechnology developments in areas such as energy storage, solar collection, nano-coated window glass, nano-based air filters and insulation materials.

Health and life sciences

The convergence of nanotechnology and biotechnology has long-term potential to transform the whole approach to healthcare. Nano-enabled techniques enable earlier, more reliable detection of diseases, accelerated drug development, targeted drug delivery, less invasive surgery, smaller functional implants, longer-lasting prosthetics, and more affordable long-term monitoring and aftercare.

A key economic driver behind nanotechnology is unlocking the hidden value of many pharmaceutical companies' already developed compounds. New drug formulations are expensive and slow to develop, while some effective compounds cannot be targeted precisely (e.g. compounds effective for treatment of toxic cancer cells are also toxic to healthy cells). So drug companies are keen to unlock the value

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[64] http://www.technologyreview.com/Nanotech/18893/?a=f

of existing intellectual property through nanotechnology processes, such as new drug delivery compounds and smaller particle sizes[65].

Industry journals estimate that in the medical world alone there are more than 150 nanotechnology-based drugs and delivery systems in development[66]. Market analysis indicates that the nanomedicine market was valued at US$53 billion in 2009, and is forecast to increase at a compound annual growth rate of 13.5%, to reach more than US$100 billion by 2014[67].

Other significant areas of development include "lab-on-chip" devices incorporating nanobiosensors (allowing rapid analysis of nanolitre-sized samples) and nanoscale contrast agents for improving the accuracy of in-vivo imaging, and culturing stem cells onto nanofibre sheets for healing neural cells and blood vessels in formerly paralysed patients.

Personal care (e.g. sunscreens, cosmetics) is an area of interest, as it involves direct consumer and public contact with nanotechnology. For sunscreens, nano-sized particles of TiO2 and ZnO provide protection without the "face-pack" look associated with conventional formulations. Nano-formulations are also increasingly used in anti-aging creams and other cosmetics. Concerns have been expressed about the unknown risks of skin penetration and/or inherent toxicity of such nanoparticles. However, evidence so far available suggests that nanoparticles currently used in cosmetic preparations or sunscreens pose no risk to human skin or human health[68].

Tackling pollution

Nanocatalysts, nanoporous filter membranes and activated nanoparticles are all contributing to efforts to tackle air, water and soil pollution[69]. Pollution prevention and reduction are resulting from more efficient use of energy and resources, better detection and sensing, materials for adsorbing pollutants and nanofiltration.

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[65] http://cientifica.eu/blog/wp-content/uploads/downloads/2011/04/058_Drug-Delivery-White-Paper.pdf

[66] http://blog.soliant.com/healthcare-news/future-effects-of-nanotech-on-health-care/

[67] http://www.bccresearch.com/report/nanotechnology-medical-applications-hlc069a.html

[68] Nohynek, G.J., Lademann, J., Ribaud, C. and Roberts, M.S. 2007. Grey goo on the skin? Nanotechnology, cosmetic and sunscreen safety. Critical Reviews in Toxicology 37: 251-277.

[69] Nowack, B. 2008. Pollution Prevention and Treatment Using Nanotechnology. *In* Nanotechnology. Vol.2. Environmental Aspects. Ed. Harald Krug. Wiley-VCH. Pp. 1-15.

Energy alternatives

A key area development is improving photovoltaic cells using a nanoparticle absorption layer sensitised by a coating with a layer of organic dye molecules (mimicking natural photosynthesis)[70]. Another interesting and potentially very significant area is the development of nanoparticles coated with a catalyst for vessels storing H_2 for fuel cell energy generation. This technique could enable safer storage and faster release of H_2 in fuel-cell powered vehicles, for example[71].

Climate change mitigation

As a platform technology (or general purpose toolkit), nanotechnology itself is unlikely to have a dramatic impact on climate change. Instead, its incorporation into larger systems, such as the hydrogen based economy, solar power technology and next generation batteries , could potentially have a profound impact on energy consumption and hence greenhouse gas emissions[72]. Significantly, many of the nanotechnology applications noted in the previous section have implications for climate change mitigation.

Governments around the world are now including nanotechnology in their overall responses to climate change and the drive to reduce greenhouse gas emissions. In the UK, for example, DEFRA has estimated that nanotechnology could reduce greenhouse gas emissions there by up to 2% in the near term and up to 20% by 2050[73] (with a similar saving being realised in air pollution).

A recent report[74] from Friends of the Earth however challenges claims that nanotechnology will lead to cleaner and more energy-efficient technologies. This report concludes that many of the claims made regarding nanotechnology's environmental performance are not matched by reality and that processes involved in manufacturing nanomaterials are indeed more energy intensive.

Risk Considerations

While nanotechnology offers huge promise for transforming many industrial processes and delivering societal benefits, such transformations may also pose

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[70] http://www.jobwerx.com/news/Archives/konarka_biz-id=947081_470.html

[71] http://www.tbp.org/pages/publications/Bent/Features/Su09Bell.pdf

[72] Esteban, E., Weberik, C., Leary, D. and Thompson-Pomeroy, D. 2008. Innovation in responding to climate change: nanotechnology, ocean energy and forestry. UNU-IAS Report. 46pp.

[73] http://www.publicservice.co.uk/feature_story.asp?id=9396

[74] http://www.foe.org/nano-climate

serious risks. The social, economic, political and ethical implications of nanotechnology are significant, as the issues involved are more complex and far-reaching than for many other innovation areas. It is unlikely therefore that current approaches for managing the introduction of new technologies will be able to deal adequately with the challenges posed by nanotechnology.

Some potential risks associated with nanotechnology include[75];

- Human health risks – due to their high surface-volume ratio and higher reactivity, nanoparticles can penetrate tissues/organs more easily, and/or cause toxic responses;
- Environmental risks – due to their potential for bioaccumulation and persistence, nanostructures could absorb smaller contaminants such as pesticides and/or create non-biodegradable pollutants.
- Manufacturing risks – radical new manufacturing methods may change market, production levels, geographic distribution of industry, as well as distribution of the work-force;
- Political and security risks – decisions made about the direction and level of nanotechnology R&D may result in insufficient investment in key areas to achieve the potential benefits, uneven or inequitable distribution of nanotechnology risks and benefits, or use in criminal or terrorist activity.

Such risks will need to be addressed trans-nationally, with a combination of;

- Improving the knowledge base;
- Strengthening risk management structures and processes;
- Promoting stakeholder communication and participation;
- Ensuring social benefits and acceptance; and
- Collaborating between stakeholders and nations.

To date, there has been little public discussion about potential risks of nanotechnology, and recent research confirms limited public concern[76]. Many nanotechnology professionals are themselves promoting more discussion on risks and instigating more work on regulation. This includes the launch of a nanotechnology regulatory document archive[77]. The OECD has established a Working Party on Manufactured Nanomaterials (WPMN) which aims to ensure that

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[75] http://www.irgc.org/IMG/pdf/PB_nanoFINAL2_2_.pdf

[76] http://medtechinsider.com/archives/22389

[77] http://nanotech.law.asu.edu/

the approach to hazard and risk assessment for nanomaterials is of a high, science-based, and internationally harmonised standard. The WPMN has established a database on manufactured nanomaterials to inform and analyse environmental health and safety research activities, developed a guidance manual for safety-testing of manufactured nanomaterials, and fostered discussion internationally on risk and safety issues (e.g. through a series of "out-reach" meetings)[78].

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[78] OECD 2011. Nanosafety at the OECD: The First Five Years 2006-2010. 15pp. http://www.oecd.org/dataoecd/6/25/47104296.pdf

5 Chemistry

Chemistry – the science of matter – is a pervasive dimension of our lives and environments. Almost every manufactured product we encounter in our daily lives embodies some form of chemical transformation. Forty-five million different chemicals are available commercially around the world. The very broad field of chemistry can be sub-divided into groups according to the type of matter being studied or the kind of study – including inorganic chemistry, organic chemistry, biochemistry, physical chemistry, materials chemistry, neural chemistry and analytical chemistry.

Chemical science, technology and innovation are critical drivers for innovation for the vast majority of industries. Chemicals are used to make a wide variety of consumer goods, as well as countless inputs to agriculture, manufacturing, construction and service industries. Polymers and plastics (i.e. derived from petrochemicals) make up about 80% of the industry's output worldwide. While the US and Europe have traditionally dominated chemical industries, China is rising fast and its petrochemical industry now ranks second in the world[79].

The challenge for considering emerging chemistry technologies therefore is setting parameters for such a review. Some significant chemistry technologies have already been noted in previous chapters (biotechnology, nanotechnology) and others will be covered (in part at least) in later chapters (e.g. waste management, clean technology) – including nanomaterials, synthetic biological compounds and solar energy harvesting materials. Indeed, virtually all the emerging research frontiers in chemistry identified by the highly regarded *Journal of Physical Chemistry Letters* referred to chemicals and chemistry for application in nanotechnology and clean energy technology[80].

This chapter therefore highlights some additional areas of emerging technology in chemicals/chemistry, mainly to illustrate the character and scope of technology development processes. Given the very diverse and diffuse nature of emerging technology in chemicals/chemistry, it is not feasible within the overall scope of this

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[79] http://www.energychinaforum.com/news/51575.shtml

[80] http://pubs.acs.org/page/jpclcd/perspectives/index.html

literature review to provide a more comprehensive or precise review of emerging research and technologies.

Industry Trends

Before focusing on specific chemical/chemistry technologies, it's worth looking at general global chemical industry trends to highlight where/how new technologies may be emerging.

The chemical industry can be broken down broadly into three segments (tiers), based on R&D intensity (R&D expenditure/sales)[81];

- low R&D intensity segment – includes companies producing high-volume, low-value added products such as mineral-based inorganic chemicals, petrochemicals and bulk polymers. This mature segment is steadily concentrating in a few world-scale production facilities, mainly in the Asian region;
- moderate R&D intensity segment – comprising companies manufacturing special purpose chemicals, such as dyes, paints, food additives and photographic materials. Many of these products are mature and involve large scale, but smaller companies can still grow as niche producers or suppliers to global production networks;
- high R&D intensity segment – comprising companies operating in high-value added, low volume chemicals, including pharmaceuticals and products from frontier areas like biotechnology and nanotechnology. Growth in this segment is driven by excellence and understanding at the molecular level, often by spin-off companies from research institutions.

Chemical sciences and the chemicals industry can no longer identify with a strictly isolated discipline. Increasingly, chemical technologies are being integrated and applied in diverse and multidisciplinary areas – e.g. electrochemistry and catalysis may be the core technologies in fuel cells, but benefits and value are likely to accrue more to the transport sector than the chemical sector.

Technology Trends

New and emerging trends in chemical industries are happening across various sector contexts[82];

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[81] Upstill, G., Jones, A.J., Spurling, T. and Simpson, G. 2006. Innovation strategies for the Australian chemical industry. Journal of Business Chemistry 3: 9-25.

- bio-based materials;
- coatings, thin films, surface treatments;
- composites;
- fibres and textiles;
- glass and ceramics;
- metals and alloys;
- nano-scale materials;
- polymers and plastics.

Major economic drivers influencing investment in research and technology development include building and construction, energy efficiency and security, and infrastructure and utilities.

The US chemicals industry, working in collaboration with the US Government and academia, has identified research priority areas[83], including;

- nanomaterials and nanotechnology – new products offering breakthrough economic, environmental and social opportunities;
- bio-separations – for improving productivity, energy efficiency and environmental performance in chemical production;
- ionic liquids (room temperature, liquid organic salts) – offer potential for 'green chemistry' applications, through catalytic reactions, separations, electrochemistry, and combined reaction/separation unit operations.

Some illustrative areas of chemical technology development are outlined below.

Chemical catalysts

Catalyis is essential for chemical industry and contributes to 90% of current chemical processes. Due to the impending depletion of fossil-based resources and increasing global demand for energy and chemicals, new catalytic systems are essential for efficient conversion of raw (both fossil and renewable) materials to valuable products and development of more sustainable manufacturing processes.

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[82] Frost & Sullivan 2010. Global Research Update – Chemicals, Materials and Food. http://www.frost.com/prod/servlet/cpo/214193271

[83] Chemical Industry Vision2020 Partnership, 2003. Report Card 2003. http://www.chemicalvision2020.org/pdfs/vision2020_annual_report03.pdf

The area of chemical catalysts is therefore a priority for chemistry R&D internationally. For example, the National Science Foundation in the US is supporting fundamental and theoretical research directed towards the synthesis and characterisation of catalysts and pre-catalysts, which may facilitate, direct and accelerate efficient chemical transformations[84]. Research in this area is exploring potential developments in solar energy conversions, for example.

Green chemistry

Sustainable chemistry – stimulating innovation at vital points along value chains simultaneously, to accelerate innovation to tackle major challenges facing society and achieve competitiveness gains. Some emerging areas include;

- eco-effective catalysts – using solid catalysts to replace hazardous reagent catalysts, and to reduce process efficiency and reduce process waste. Such catalysts can include zeolite catalysts for the ethylation of benzene, and titanium silicate as an oxidation catalyst in the manufacture of hydroquinone;[85]
- supercritical fluids and ionic liquids – new solvents and reaction media offering non-volatile and non-flammable options for a wide variety of chemical applications, including electrolytes in batteries, lubricants, solvents and catalysis in synthesis, matrices for mass spectroscopy, solvents to manufacture nano-materials, extraction and gas absorption agents;[86]
- catalysts for producing hydrogen – low-cost oxygen-producing catalysts mimicking photosynthesis could enable small-scale hydrogen production for application in fuel cells;[87]
- benign solvents – replacing harmful organic solvents that are used widely in many current chemical processes.[88]

Chemicals in packaging

Packaging materials can include various chemicals – including some that are potentially harmful. Plastic wrappers, food cans and storage vessels deposit at least two potentially harmful chemicals into our food – bisphenol A (or BPA) and a

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[84] http://www.nsf.gov/mps/che/realign/brochure.pdf

[85] Oyama, S.T. 2008. Mechanisms in Homogenous and Heterogeneous Epoxidation Catalysis. Elsevier. 487pp.

[86] Keskin, S., Kayrak-Talay, D., Akman, U. and Hortacsu, O. 2007. A review of ionic liquids towards supercritical fluid applications. Journal of Supercritical Fluids 43: 150-180.

[87] http://www.gizmag.com/electrode-materials-hydrogen-fuel/15118/

[88] Brummond, K.M. and Wach, C.K. 2007. Environmentally benign solvent systems: Toward a greener [4+2] cycloaddition process. Mini-reviews In Organic Chemistry 4: 89-103.

phthalate called DEHP – which are known to disrupt mammalian hormonal systems[89]. Imported products (not only food) could therefore be carrying various potentially harmful chemicals with them.

New packaging technologies aimed at reducing such chemical risks are therefore emerging. This includes biopolymers – as an alternative to the oil-derived polymers that have featured heavily in packaging over recent decades. The biopolymers industry has been evolving rapidly, from an emerging technology, passing through concerns about demand and supply, the food or fuel debate and the availability of raw materials, to an increasing number of applications in packaging, as well as in other industrial areas such as medicine (e.g. medical devices, tissue engineering, drug delivery)[90].

China – a special case

As chemical industry in China expands to satisfy domestic demand, companies are achieving international competitiveness through scale and efficiency, and are accordingly looking internationally as well for new export opportunities. This means chemicals produced in China will increasingly substitute those from other markets. While not based strictly on new or emerging technologies, such chemicals will nevertheless appear 'new to the market', at least in terms of formulations.

China is accordingly becoming an important centre for R&D in the chemicals industry, with much of this activity directed towards commercial application and customisation to meet the needs of China's increasingly sophisticated domestic market. International companies are also looking to China and its growing R&D capability. For example, Syngenta announced in 2008 that it will invest US$65 million over 5 years in a new R&D centre in Beijing.

Some example areas of chemical development in China are outlined below.

Herbicides and pesticides

China now leads the world in the production of herbicides and pesticides[91]. Research and technology development is largely driven by herbicide and pesticide companies, often supported by universities and research institutes of the Chinese

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[89] Rudel, R.A., Gray, J.M., Engel, C.L., Rawsthorne, T.W., Dodson, R.E., et al. 2011. Food Packaging and Bisphenol A and Bis(2-Ethylhexyl) Phthalate Exposure: Findings from a Dietary Intervention. Environmental Health Perspectives doi:10.1289/ehp.1003170.

[90] Allied Development, 2010. Biopolymers in Packaging 2010 to 2014: Global markets, environmental impacts and technologies.

[91] China Chemical Reporter, 2002. China opens doors to the world: Domestic pesticide producers focus on the expired patents.

Academy of Sciences. For example, the Shanghai Pesticide Research Institute[92] is recognised as a leading pesticide research centre in China. It does R&D on chemical synthesis of agricultural antibiotics, bioactive screening of new compounds, and mode of action of new pesticides, including;

- chemical synthesis – such as isoxathion and ethofenprox;
- bioengineering – such as agricultural antibiotics enzymes and biofermentation of acrylamide;
- formulations – such as microemulsions of chlorpyrifos.

Research to develop 'green' pesticides is expanding in China. The Science and Technology Plan (within China's Five-Year Plan) includes a 'green chemical pesticide research program'. The initial focus of this program has been to establish China's capability to conduct basic research in the discovery of 'green' crop protection chemicals. This has resulted in new core technologies in chemoinformatics and computation-aided pesticide design, and bioassay methodologies[93].

Coal to chemicals

'Coal to chemicals' uses coal as raw material instead of crude oil, and requires new-generation technology to turn it into gas, liquids, solid fuels and other chemical products[94]. From a cost perspective, coal to chemicals enjoys an obvious advantage as oil is four times as expensive as coal. As prices of imported oil climbed over the lasts decade, Chinese chemical makers began using coal gasification to make olefins (the basic precursor of many polymers and plastics). Western companies (including Dow Chemicals) are advancing their technology in coal to chemicals in China, lured by China's ample supply of coal.

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[92] http://www.chinachemnet.com/spri/introduction-e.html

[93] Qian, X., Lee, P.W. and Cao, S. 2010. China: forward to the green pesticides via a basic research program. Journal of Agricultural and Food Chemistry 58: 2613-2623.

[94] http://gulfnews.com/business/markets/chinese-economy-to-be-fired-by-coal-to-chemicals-1.739968

6 *Information and Communications Technologies*

Information and Communications Technologies (ICTs) may not seem immediately relevant to biological and chemical risk issues. However, the pervasive nature of these technologies, affecting every aspect of our lives, means that some understanding of emerging trends and developments is relevant within the context of this review.

Over the last 30 years or so, substantial changes in ICTs have transformed virtually every aspect of our lives – including business, education, entertainment, health care, environmental management, and government itself. The scale, pace and impact of change is perhaps best represented by "Moore's Law" – that processing speed and capacity of silicon chips will approximately double every 18 months. With the experience of such ubiquitous change over recent years, it would be tempting to expect to see simply "more of the same" and therefore overlook the significance of future impacts of continued development of ICT.

This review therefore includes some brief commentary of key areas of development in ICT that could be expected to have significant impacts – in terms of paradigm changes, system interruptions or interdependency changes – on technology development in other areas. The review does not attempt to cover incremental changes (although according to Moore's Law, such changes are themselves relatively large and rapid).

Key Drivers for ICT Research

ICT is widely regarded as a key driver of innovation and productivity across productive and service sectors of the economy, and is therefore often referred to as a "key engine of growth". The ICT sector has also been identified as a potential major player in the fight against climate change, particularly through increasing energy efficiency. ICT is also likely to play a major role in providing responses to societal challenges such as the ageing population, sustainable health and social care, inclusion, education and security. There is also increasing evidence of ICT impacts on social behaviours (e.g. social networking) that in turn are likely to affect democratic processes and creativity.

The changing mode of ICT's impact on our lives is perhaps best illustrated through some recent trends and developments in internet technologies. In particular open web-based innovation platforms, cloud computing, and internet-enabled "smart" infrastructures are having dramatic impacts on wide ranging economic and social activities.

The path forward for ICT is however uncertain, as many technology developments are at a cross-road. Radical breakthroughs in ICT will increasingly rely on deep synergies with other disciplines (e.g. nanotechnology, biotechnology, social science, economics) and with the arts and humanities. This is likely to involve new attitudes and novel collaborations between a broad diversity of interested parties, which in turn are likely in turn to have a significant impact on future ICT.

Core Technologies

The future internet

Over the past 15 years, the internet has become a vital part of everyday life for over 2 billion people around the world (likely to expand to 7 billion by 2020). A recent report[95] has highlighted four powerful forces shaping the future of the internet;

- Tension between vested interests of different stakeholders – commercial (network operators, service providers and content providers), governments, and individual users – who all tend to see it as "their" internet. Innovation in internet infrastructure has slowed down since the large commercial players gained sufficient market power, around 2005;
- A shift in the context of the internet – beyond a simple technical context (of bits and bytes) to a much wider and pervasive social, cultural, political, economic and commercial (non-technical) context. Future internet infrastructure is more likely to be shaped by these wider contexts than simple technical drivers;
- Governance and regulation – policy-makers and regulators need to become more knowledgeable about the internet and its business models, to ensure future genuinely global governance, and technological and network neutrality;
- The future user – a shift from technology-driven design to user-needs driven design, involving an emphasis on the whole human interface environment (including user motivation, digital literacy, signalling forms).

Major collaborative research initiatives on the future of the internet are being carried out in Europe (FIRE – Future Internet Research and Experimentation[96]) and the US (FIND – Future Internet Design[97]).

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[95] http://cordis.europa.eu/fp7/ict/fire/docs/tafi-final-report_en.pdf

The future computer

Computer architecture is at a cross-road, caused by several key trends;

- Technology – the long-anticipated slowing in "Moore's Law" improvements makes it increasingly difficult to extract more computer performance by employing more transistors on chip;
- Applications – the growth in rich multimedia applications and data intensive computing, along with mobile/embedded computing at one extreme and warehouse-scale data at the other all adds up to a need for new thinking on architectural interfaces; and
- Changing performance expectations – consumers are paying more attention to reliability and security, rather than just processing capacity and speed.

Major companies with stakes in computer architecture (e.g. Microsoft, Intel, Apple) are investing significant amounts in finding solutions[98]. While the nature or shape of such solutions is not yet clear, they are nevertheless likely to have significant impact within the next 10-15 years, given the relatively rapid rate of development of ICTs overall.

The growth of cloud computing is likely to be the most significant trend affecting the "future computer" over the next 10-15 years. A solid majority of technology experts and stakeholders participating in the 4th Future of the Internet survey expect that by 2020 most people will perform most computing and communication activities (e.g. access software applications, share and access information) through connections to servers operated by outside firms (rather than depending mainly on tools and information housed on their individual personal computers or workplace-based servers)[99].

Cloud computing is already well established, through social networking, webmail, blogging, video and picture sharing, and on-line auction services. Its advantages include allowing users to have easy, instant and individualised access to tools and information they need wherever they are and locatable from any network device.

Cloud computing does introduce new risks – to individuals, enterprises and governments. In particular, by devolving "gatekeeping" of data and services to third

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[96] http://cordis.europa.eu/fp7/ict/fire/

[97] http://www.nets-find.net/

[98] http://www.cra.org/ccc/docs/init/Computer_Architecture.pdf

[99] http://pewinternet.org/Reports/2010/The-future-of-cloud-computing.aspx

parties, cloud computing also presents new reliability and security risks. There is also a risk that cloud dominance by a small number of large firms may constrict the internet's openness and its capacity to inspire innovation.

New frontiers

Our experience of the scope of ICTs is constantly being challenged, as new frontiers of development and application are opened. Some key areas to watch in coming years include;

- Cognitive systems and robotics – engineering and designing artificial cognitive systems and robotic systems[100]; and
- Intelligent biosciences – the convergence of ICT with biotechnology (i.e. bioinformatics) and nanotechnology (i.e. material convergence, such as integrated silicon electronics and photonics) is paving the way for intelligent biosciences (by linking material convergence and bioinformatics)[101].

Applications

ICT and future industry

ICT is likely to drive significant changes in industry through;

- "Smart" factories – including control and sensor-based systems and industrial robots;
- "Virtual" factories and enterprises – allowing innovation and higher management efficiency in networked operations;
- Digital manufacturing – including product life-cycle management, modelling, and optimisation[102].

Such changes are likely to affect physical location and ownership of future businesses, which in turn will have economic and social implications (e.g. employment).

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[100] Tikhanoff, V., Cangelosi, A., Fitzpatrick, P., Metta, G., Natale, L. and Nori, F. 2008. An open-source simulator for cognitive robotics research: the prototype of the iCub humanoid robot. PerMIS'08, August 19-21.

[101] http://www.futuretechnologycenter.eu/content/lifesc.php

[102] http://cordis.europa.eu/fp7/ict/programme/challenge7_en.html

ICT and future social development

ICT will have major impacts in a wide range of social areas, including education, healthcare, social and economic inclusion, and governance. Some key areas of development include;

- Education – moving e-learning beyond a simple complement to traditional learning approaches. Key challenges therefore remain in maximising the learning opportunities and impacts possible through ICT. There is evidence of interdependency between impacts of ICT in education and access to ICT in wider contexts[103];
- Healthcare – facilitating better access to healthcare – wherever and whenever, through databases, innovative telemedicine and personal health systems[104];
- Social and economic inclusion – enabling people to connect, engage and develop socially and economically. Reducing or removing the "digital divide" is a pre-requisite for outcomes in this area[105]. Governments and businesses working together have the potential to develop and deploy relevant ICT processes and solutions;
- Governance – eGovernment programmes are widespread around the world[106]. From an initial focus on streamlining citizens' interactions with government, initiatives have shifted to design and delivery of citizen-centric services and are increasingly democratising government processes and roles.

ICT and the future environment

ICT innovation is widely regarded as a key element to spur "green" economic growth, thereby improving environmental performance and climate change across the economy. New ICT developments and applications are likely to be of most significance in industry areas with the potential to contribute most to smarter environmental and economic strategies and applications (e.g. clean energy).

A primary challenge however, is to reduce the negative impacts of ICTs on the environment. ICTs can damage the environment – through increasing energy use (e.g. the ICT sector's contribution to global CO2 emissions is expected to double by

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[103] http://ftp.jrc.es/EURdoc/JRC47246.TN.pdf

[104] http://ec.europa.eu/information_society/activities/health/index_en.htm

[105] Warschauer, M. 2003. Technology and social inclusion: rethinking the digital divide. MIT Press. 260pp.

[106] United Nations E-Government Survey 2010. 125 pp. ISBN: 978-92-1-123183-0.

2020 under business-as-usual scenarios[107]), extraction of essential and valuable metals (e.g. extraction of tantalum played a role in funding the civil war in the Democratic Republic of Congo between 1996-2003[108]), and vast quantities of e-waste (e.g. hazardous metals like lead, mercury and cadmium) result when short life-span ICT equipment is retired.

Future ICT developments are likely to contribute to improved environmental outcomes in three ways;

- Decreasing the direct effects on the environment of the production, distribution, operation and disposal of ICTs through improved energy and materials efficiency, through an integration of redesign, reuse and recycling[109];
- Increasing the enabling effects of ICTs on the development of the green economy through improvements in the efficiency of production, distribution and consumption of goods and services throughout the economy and society (especially energy efficiency and dematerialisation)[110]; and
- Supporting systemic effects that result in transformation of the behaviour, attitudes and values of individuals as citizens and consumers, economic and social structures and governance processes[111].

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[107] The Climate Group 2008. Smart 2020: Enabling the Low Carbon Economy in the Information Age. www.smart2020.0rg/_assets/files/02_Smart2020Report.pdf

[108] Vetter, T. 2009. Resource Wars and Information and Communication Technologies, paper by the International Institute for Sustainable Development. www.iisd.org/pdf/2008/com_resource_wars.pdf

[109] http://www.step-initiative.org/

[110] http://www.nordicenergysolutions.org/solutions/green-ict/dematerialisation-itc-enabled-reduction-of-energy

[111] http://www.epractice.eu/community/envirodemocracy

7 *Waste Management*

Waste management is an issue of increasing significance across all countries, as ways of reducing the negative impacts of waste on health, the environment or aesthetics are sought. Waste management methods will vary with the nature of the waste involved, with primary responsibilities typically assigned to local government authorities for non-hazardous residential and institutional waste, and to generators for non-hazardous commercial and industrial waste.

Innovative technologies are progressively transforming the management of urban and industrial wastes. The development of new and emerging technologies is being driven by the need to find alternatives to land-filling and mass-burn incineration. Some key areas of development internationally include energy recovery (including biodiesel and fuel cells), recycling (including biological reprocessing) and waste minimisation (avoidance and reduction). Some more specific technologies have been developed to manage particular types of waste (e.g. bioremediation) or for specialised treatment. Perhaps the most significant area of technology development is in developing better understanding of pathways, processes and dynamics involved in different waste management options – aided particularly by life cycle assessment technology.

Life Cycle Assessment (LCA)

There is increasing interest among those responsible for managing waste in designing strategies for integrated, sustainable waste management "systems". Life cycle assessment (LCA) methodologies can be used as an input to decision-making regarding the choice of waste management solutions. A LCA provides an overview of the environmental benefits and costs of different management options and makes it possible to compare the potential environmental impacts of these options.

LCA methodologies are however constrained by limited current scientific knowledge of the fate of substances contained in waste, disposed through incineration, landfill or recycling. LCA tools are being developed specifically for waste management issues in various countries, making as much use as possible of the scientific knowledge that is available. Some examples include;

- Waste-integrated Systems for Assessment of Recovery and Disposal, WISARD (United Kingdom and France)112 – models various kinds of waste management system, compiles life cycle inventories, performs analyses to identify "data hot spots", and conducts life cycle impact assessment according to a set of different methods;
- EPIC/CSR Integrated Waste Management Model (Canada)[113] – uses life cycle analysis to quantify energy consumed and emissions released from a waste management systems, for specific municipalities/local authorities;
- Life Cycle Inventory Model for Integrated Waste Management, IWM-2 (United Kingdom)[114].

The EASEWASTE LCA model[115], developed at the Technical University of Denmark, is a good example of how complex waste management decisions can be integrated into a user-friendly decision-support tool. EASEWASTE supports full LCA of any user defined residential, bulky waste or garden waste management system. The model focuses on the major components of the waste and reviews each component in terms of the available waste management options, including bio-gasification and composting, thermal treatment incineration, use-on-land, material sorting and recycling, bottom and fly ash handling, material and energy utilisation and land-filling. Experience with EASEWASTE has shown that waste management systems can be designed in an environmentally sustainable manner where energy recovery processes lead to substantial avoidance of emissions and savings of resources.

LCA therefore represents a key tool for identifying critical points for influence and intervention within overall waste management strategies, and in turn helps prioritise and focus responses – for example in the various layers of the waste management hierarchy. Indeed the real value of LCA may lie in the potential impact on "social" responsibility – within communities and businesses – for waste management.

Energy Recovery

Generating energy from waste is a "win-win" – reducing the direct environmental impacts of waste and reducing dependence on other non-renewable energy sources.

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[112] https://www.ecobilan.com/uk_wisard.php

[113] http://www.iwm-model.uwaterloo.ca/

[114] McDougall, F.R., White, P.R., Franke, M. and Hindle, P. 2001. Integrated Solid Waste Management: A Life Cycle Inventory, 2nd Edition. Wiley-Blackwell, 544pp.

[115] Bhander, G.S., Christensen, T.H. and Hauschild, M.Z. 2010. EASEWASTE – life-cycle modelling capabilities for waste management technologies. International Journal of Life Cycle Assessment 15: 403-416.

As energy prices and demand for waste disposal capacity increase, communities are increasingly looking to energy recovery technologies to meet their disposal needs while also producing energy with minimal environmental impact. A comprehensive analysis of energy recovery from municipal solid waste (MSW) recorded that landfill-gas-to-energy and waste-to-energy projects represented about 14% of US non-hydro renewable electricity generation in 2008[116].

Recycling

Waste materials that are organic in nature (e.g. plant material, paper products) can be recycled using biological composting and digestion processes to decompose organic matter, resulting in material that can be recycled as mulch or compost for agriculture or landscaping purposes. Biological reprocessing aims to control and accelerate the natural decomposition process.

Biological reprocessing systems are based on aerobic or anaerobic processes, usually with large-scale and capital-intensive facilities. This means the technology is generally is more advanced in large cities in more developed countries. In the United Kingdom, for example, a sustainable biological reprocessing "sector" is developing rapidly to transform the millions of tonnes of household biodegradable waste being diverted from landfill into benign and often marketable products.

The environmental economics of waste recycling should consider not only the immediate costs:benefits associated with the waste itself, but also the climate change impacts of different wast management processes. A recent study analysing release and savings of CO_2 at different stages, demonstrated that, for green waste, composting saved as much CO_2 as energy recovery[117], showing that recycling and energy recovery should be seen as complementary options for waste management.

Significant technologies for recycling (such as those noted above) often apply after waste has been collected. The overall success of recycling technologies however can depend strongly on households' participation. An important research area therefore is developing an understanding of social attitudes to recycling – and the associated identification of incentives and/or sanctions. One such study – in Portugal – found that postive attitudes toward recycling and information are important factors in explaining households' participation[118].

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[116] Kaplan, P.O., Decarolis, J. and Thorneloe, S. 2009. Is it better to burn or bury waste for clean electricity generation? Environmental Science and Technology 43: 1711-1717.

[117] Kranert, M., Gottshall, R., BNruns, C. and Hafner, G. 2010. Energy or compost from green waste? A CO_2-based assessment. Waste Management 30: 697-701.

[118] Vincente, P. and Reis, E. 2008. Factors influencing households' participation in recycling. Waste Management & Research 26: 140-146.

Bioremediation

Bioremediation involves the application of microorganism metabolism to remove pollutants – either on-site or elsewhere after the removal of contaminated material. Examples of bioremediation technologies include phytoremediation, bioventing, bioleaching, bioreactor, bioaugmentation, biostimulation and rhizofiltration. Microorganisms used in bioremediation are known as "bioremediators".

Bioremediation has the potential to restore contaminated environments inexpensively. However a lack of information about factors controlling the growth and metabolism of microorganisms in polluted environments often limits its implementation. This means there is a need for more detailed understanding of complex sub-surface environments, including geochemistry, biological interactions, impacts of disturbance, bio-geo-chemical dynamics.

Combining models that can predict the activity of microorganisms that are involved in bioremediation with existing geochemical and hydrological models should transform bioremediation from a largely empirical practice into a science. Recent research advances may soon offer new insights and ability to culture important microorganisms. In particular, researchers are now able to culture microorganisms important for bioremediation and evaluate their physiology using a combination of genome-related experimental and modelling techniques[119]. In addition, new environmental genomic techniques offer the possibility for similar studies on as-yet-uncultured organisms.

A major bioremediation research programme[120], which is illustrative of international bioremediation research developments, is being carried out at the Oak Ridge National Laboratory (managed for the US Department of Energy). This programme involves multi-scale (molecular to catchment) investigations on the rates and mechanisms of targeted immobilisation and natural attenuation of metal, radionuclide and co-contaminants in the subsurface. Such research highlights the need for site- and contaminant-specific research knowledge to underpin the development of appropriate and effective bioremediation strategies.

Bioremediation research is being supported by on-going developments in underpinning technologies (e.g. biotechnology, nanotechnology). For example:

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[119] Lovley DR (2003) Cleaning up with genomics: applying molecular biology to bioremediation. Nature Reviews: Microbiology 1(1):35-44.

[120] http://www.esd.ornl.gov/orifrc/

- Bioremediation (using microorganisms to remove environmental pollutants) can be enhanced using genetically modified organisms[121];
- Biodegradation of industrial effluents is being enabled with the use of microoganisms targeted at specific waste compounds[122];
- Nanoscale iron particles for environmental remediation[123]; and
- A recent review of the potential of metabolomics tools in bioremediation studies found that the better understanding of biodegradation processes enabled through such tools had the potential to significantly extend and enhance existing bioremediation approaches[124].

Specialised Technologies

There are many, many other specialised technologies developed and applied for different waste situations. Some illustrative examples include:

- Specialised filter materials for removing pollutants from landfill leachate[125];
- Microbial immobilisation in waste water[126];
- Biochar production (through pyrolysis) offering an attractive solution to management of biodegradable wastes in a sustainable way, while also enhancing soil enrichment and decreasing net CO_2 emissions[127];

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[121] http://www.molecular-plant-biotechnology.info/biotechnology-environments/bioremediation-phytoremediation/bioremediation-using-genetically-engineered-microbes-gem.html

[122] Lin, J., Reddy, M., Moorthi, V. and Qoma, B.E. 2008. Bacterial removal of toxic phenols from an industrial effluent. African Journal of Biotechnology 7: 2232-2238.

[123] Zhang, W.X. 2003. Nanoscale particles for environmental remediation: An overview. Journal of Nanoparticle Research 5: 323-332.

[124] Villas-Boas, S.G. and Bruheim, P. 2007. The potential of metabolomics tools in bioremediation studies. OMICS 13: 305-313.

[125] Krangsepp, B.M., Svensson, L., Martenson, D., Rosenquist, W., Hogland, L. and Mathiasson, L. 2008. Column studies aiming at identification of suitable filter materials for pollutant removal from landfill leachate. International Journal of Environmental and Waste Management 2: 506-525.

[126] Yang, F., Wang, X., Zhang, H., Wang, Y. and Gao, M. 2011. A review on the essential role of substrate on aerobic granulation. International Journal of Environment and Waste Management 7: 67-79.

[127] Ibarrola, R. 2009. Pyrolysis for waste management: A life cycle assessment of biodegradable waste, bioenergy generation and biochar production in Glasgow and Clyde valley. MSc Thesis: University of Edinburgh.

- Use of adsorbents (e.g. "red mud") for removing toxic pollutants (e.g. dyes, phenolic compounds) from water and waste-water[128].

A recent study highlighted the importance of taking a broad and integrated approach to managing wastes, particularly in relation to contaminated soil and groundwater[129]. Effective remediation, for example, often involves incorporating techniques or even whole new technologies into an existing technology as a treatment train. Critically, economic and decision-making tools play a vital role in waste management, particularly for optimising technology choice and application.

Reducing waste (and energy use) in chemical processes (in various areas of manufacturing) is a key focus for emerging chemistry/chemical technologies. In the pharmaceutical industry, for example, classical methods produce, on the average, about nine times as much disposable waste as desired product. This has led to the demand for procedures that have "atom efficiency", in which all the atoms of the reacting compounds appear in the product. The use of multicomponent processes could contribute to this goal. Conventional process development has focused on optimising single reactions. New processes that involve reaction cascades, where the product of one reaction feeds into the next, will permit more efficient production of industrial or biomedical products. The future will also likely see greater use of more abundant or renewable raw materials and greater re-use of materials such as CO_2, salts, tars and sludges which are currently discarded as waste.

There is already good evidence of manufacturers replacing the use of organic solvents in processing with the use of supercritical CO_2 (s CO_2) – an inert molecule that has excellent performance attributes as a solvent[130]. This is occurring in several applications – decaffeination of coffee, extraction of flavours, fragrances and neutriceuticals, production of certain plastics, and coatings.

Waste Minimisation

Minimising the initial generation of waste could be seen as the "holy grail" of waste management research and technology development.

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[128] Bhatnagar, A., Vilar, V.J.P., Botelho, C.M.S. and Boaventura, R.A.R. 2011. A review of the use of red mud as adsorbent for the removal of toxic pollutants from water and wastewater. Environmental Technology 32: 231-249.

[129] Caliman, F.A., Robu, B.M., Smaranda, C., Pavel, V.L. and Gavrilescu, M. 2011. Soil and groundwater cleanup: benefits and limits of emerging technologies. Clean Technologies and Environmental Policy 13: 241-268.

[130] The National Academies 2003. Beyond The Molecular Frontier: Challenges for Chemistry and Chemical Engineering. http://dels-old.nas.edu/dels/rpt_briefs/molecular_frontier_final.pdf

Internationally, a significant area of research focus is influencing social attitudes regarding the generation of waste. While social marketing is a valuable tool in this regard, making meaningful progress within reasonable time-frames may depend on more active approaches. For example, a study in Ireland showed that action research involving active waste minimisation exercises in the home offered enhanced learning opportunities for participating householders techniques as well as nuanced information for policy makers[131]. Crucially, this study also found that commitment of waste service providers to respond to the findings of participants was vital.

Strengthening "producer responsibility" for reducing wastes (e.g. packaging) is an example of a "systems"-based technological solution. A recent review of extended producer responsibility for packaging wastes and waste electronic equipment, comparing implementation and the role of local authorities across Europe, found that that while approaches varied, results were significantly more positive where local authorities were engaged in the design and implementation of national systems[132]. Local differences reflected fears on the part of industry about associated costs and contrasting opinions about the legitimacy of local authorities as stakeholders.

Key areas of development include the application of new fields of technology (e.g. biotechnology, nanotechnology) to transform industrial and consumer processes. Relevant technologies include:

- Replacing chemical processes with biological processes (e.g. enzymes rather than chemicals for degrading and modifying lignin in the paper industry)[133];
- Replacing environmentally "risky" raw materials with biologically-derived alternatives (e.g. plastics can be produced using enzymatically- or microbially-altered sugars rather than oil-based raw materials)[134]; and
- Nanocomposites for biodegradable plastics[135].

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[131] Fahy, F. and Davies, A. 2007. Home improvements: household waste minimisation and action research. Resources, Conservation and Recycling 52: 13-27.

[132] Cahill, R., Grimes, S.M. and Wilson, D.C. 2011. Extended producer responsibility for packaging wastes and WEEE – a comparison of implementation and the role of local authorities across Europe. Waste Management & Research 29: 455-479.

[133] Risna, R.A. and Suhirman 2002. Ligninolytic enzyme production by *Polyporaceae* from Lombok, Indonesia. Fungal Diversity 9: 123-134.

[134] Nguyen, H.T., Mishra, G., Whittle, E., Bevan, S.A., Merlo, A.O., Walsh, T.A. and Shanklin, J. 2010. Metabolic engineering of seed ⎤-7 fatty acid accumulation. Plant Physiology 154: 1897-1904.

[135] Maiti, P., Batt, C.A. and Giannelis, E.P. 2007. New biodegradable polyhydroxybutyrate/layered silicate nanocomposites. Biomacromolecules 8: 3393-3400.

8 Clean Energy

As world demand for energy grows (it is expected to double over the next 50 years), incremental improvements in existing energy networks are unlikely to be sufficient to supply this demand in a sustainable way. Finding sufficient supplies of "clean energy" for the future is therefore one of society's most critical challenges.

New "clean energy" technologies may not be immediately relevant to a consideration of biological and chemical risks. However, there is a strong overlap between some of these emerging technologies and the biological and chemical technologies noted in earlier sections. It is therefore worthwhile including a broad overview of emerging "clean energy" technologies within this review.

"Clean energy" can be generally described as a diverse range of products, services and processes that harness renewable materials and energy sources, dramatically reduce the use of natural resources, and cut or eliminate emissions and wastes. It generally involves developing energy sources and applications that have a smaller environmental footprint and minimise pollution, and includes recycling, renewable energy, information technology, transportation technologies, and energy-efficient devices and processes.

Solar Energy

The huge gap between our present use of solar energy and its enormous undeveloped potential defines a great challenge for clean energy research. Globally, only a small fraction of the solar energy available is captured and utilised for energy. More energy from sunlight strikes the earth in one hour (4.3×10^{20} J) than all the energy consumed on the planet in a year (4.1×10^{20} J)[136]. While some of this solar resource is currently exploitedolar electricity accounts for less than 2% of the world's electricity and solar fuel from biomass provides less than 2% of the world's energy.

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[136] Office of Science, US Department of Energy, 2005: Basic Research Needs for Solar Energy Utilization. 261pp.

Solar energy can utilised through three primary conversion processes:

- Solar electricity;
- Solar fuels; and
- Solar thermal systems.

Solar electricity

The main challenge in converting solar energy into electricity via photovoltaic solar cells lies in dramatically reducing the cost/watt of delivered solar energy – by a factor of 5-10 to compete with fossil and nuclear electricity, and by a factor of 25-50 to compete with primary fossil energy. New materials to efficiently absorb sunlight, new technologies to harness the full spectrum of wavelengths in solar radiation, and new approaches based on nanostructured architectures are revolutionising the technology used to produce solar energy. Several scientific journals regularly publish new research in this area (e.g. *Materials*, *Applied Physics Letters*) as well as a journal dedicated to publishing new research in this area – including *Solar Energy Materials and Solar Cells* (Elsevier).

Efficient solar cells typically have several layers of semiconductor materials, each tuned to convert different colours of light into electricity. Researchers at Lawrence Berkeley National Laboratory (USA) have now made, using common and inexpensive manufacturing techniques, a single semiconductor that performs almost the same job[137].

Several research groups are developing semiconductor materials that harness more of the energy in sunlight, for example using thin-film solar cells incorporating nano-particle technology[138], or new compounds such as gallium arsenide[139]

Solar fuels

Storage of solar-generated electricity (e.g. to overcome generation variations due to cloudiness and day-night cycles) is an important area of research to underpin more cost-effective development of solar energy technology systems. The most attractive and economical method of storage is conversion to chemical fuels.

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[137] http://www.cleanenergyauthority.com/solar-energy-news/lawrence-berkeley-study-could-riase-pv-efficiency-013111/

[138] K.R. Catchpole and S. Pillai, "Absorption enhancement due to scattering by dipoles into silicon waveguides", Journal of Applied Physiology, in press.

[139] Jongseung Yoon, 2010. GaAs photovoltaics and optoelectronics using releasable multilayer epitaxial assemblies, Nature, Volume: 465, Pages: 329-333.

Historically, the cheapest form of storing solar fuel is as biomass, but energy demand has far outpaced biomass supply over the last couple of centuries. The use of existing types of plants requires large land areas to meet a significant portion of primary energy demand – thereby constraining the contribution biomass can make towards meeting global energy demand. Hence key lines of research are (i) applying biotechnology to design plants and organisms that are more efficient energy conversion "machines"[140], and (ii) designing highly efficient, all-artificial, molecular-level energy conversion machines exploiting the principles of photosynthesis[141]. A key element in both approaches is using structural biology, genome sequencing and proteomics to better understand and manipulate biological conversion of solar radiation to sugars and carbohydrates.

Artificial nanoscale assemblies of new organic and inorganic materials, replacing natural plants or algae, can now use sunlight to directly produce H2 by splitting water and hydrocarbons via reduction of atmospheric CO2[142]. But there is still a huge gap between this laboratory-scale research and a deployable technology.

Solar thermal systems

The key challenge in solar thermal technology is to identify cost-effective methods to convert sunlight into storable, dispatchable thermal energy. In particular, new materials that can function at the high temperatures associated with thermal reactions (e.g. 3000°C or more), new chemical conversion sequences (such as those used to split water to produce H2 using heat from fission reactors) to convert focused solar thermal energy into chemical fuel, or new solar "engines" (turbines driven by solar heat at lower solar concentration temperatures) for efficient, mechanical production of electricity are needed to drive applications of this technology. Recent developments in this area can be illustrated using the research carried out at the Argonne National Laboratory of the US Department of Energy[143].

The research involved in dramatically transforming the economics of solar energy is very complex, increasingly inter-disciplinary in nature, and anticipates long time-frames for development and deployment of requisite technologies. Researchers and their technology partners are nevertheless optimistic that significant progress can be made over the next 15-35 years, based substantially on continuing, rapid worldwide progress in nanoscience and genetic technologies. As such progress is likely to challenge current regulatory systems in various jurisdictions, it may be prudent to

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[140] http://www.jouleunlimited.com/

[141] http://www.efrc.unc.edu/research/index.html

[142] US Government NSTC Committee on Technology 2010. National Nanotechnology Initiative Signature Initiative: Nanotechnology for Solar Energy And Conversion.

[143] http://www.anl.gov/solar/research/concentrat_sunlight/index.html

ensure New Zealand's regulators both keep a close eye on research developments internationally and engage with regulators in other jurisdictions as new "global" standards for regulating such technologies emerge.

Wind Energy

While wind energy technology is now well established, there is still significant research effort aimed at improving the technological performance and economic efficiency/value of wind energy generation systems. The main areas of endeavour include:

- Improving power production (output);
- Reducing capital cost;
- Improving plant reliability and lower operating costs;
- Eliminating barriers to large-scale deployment.

System developments

The literature shows three main areas of research:

- Wind power systems – particularly turbine (rotor, gearbox, tower) design – for large, medium and small turbines. Research in this area generally involves a linear trajectory for iteratively scaling up and improving current technologies.
- Wind energy integration – systems approaches for large-scale integration of wind energy generation into national/international power grids. Research in this area generally involves integrating generation technology and transmission technology, with a strong focus on information systems and business model design.
- Off-shore deployment of wind energy technology and systems – giving access to much larger potential energy sources. This is a key area of development, with the potential to significant change the scale and economic impact of wind energy.

Offshore wind energy

Offshore wind energy projects are not entirely new. Shallow-water projects have been underway in Europe for more than a decade now, applying technology that has essentially evolved from land-based wind energy systems. Significant opportunities remain for tailoring the technology to better address key differences in the off-shore environment, particularly for deep-water floating systems which are still at very early stages of development[144].

There are many challenges associated with opportunities for advancing offshore wind technologies;

- Extending technologies developed for land-based systems – While turbine blades can be much large without land-based transportation and construction constraints, enabling technology is needed to allow construction of blades of more than 70 m in length. Blades may also be allowed to rotate faster offshore, as blade noise is less likely to disturb people and communities. Faster rotors operate at lower torque, which means lighter, less costly drive-train components.
- Challenges specific to offshore environments – Turbines materials and construction need to be resistant to corrosive salt waters, resilient to storms and waves, and co-exist with marine life and activities. With increasing distance from shore, such challenges may increase exponentially, due to increased water depth, exposure to more extreme ocean conditions, long-distance electrical transmission on high-voltage submarine cables, and turbine maintenance at sea.

The European Technology Platform for Wind Energy (TPWind), sponsored by the European Commission (through its Framework 6 programme) has developed a strategic research agenda for off-shore wind energy[145]. This agenda focuses on five research topics:

- sub-structures;
- assembly, installation and decommissioning;
- electrical infrastructure;
- turbines; and
- operations and maintenance.

Perhaps more interesting than the research topics, three common themes have been identified which will affect the entire development of the offshore wind energy opportunity. These are:

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[144] National Renewable Energy Laboratory, 2010: Large-scale offshore wind power in the United States – Assessment of opportunities and barriers. www.osti.gov/bridge

[145] European Wind Energy Technology Platform, 2008: Strategic Research Agenda, Market Deployment Strategy - www.windplatform.eu/fileadmin/ewetp_docs/Bibliography/SRA_MDS_July_2008.pdf

- Safety – safe operation of offshore facilities, and the safety of staff involved in all stages of developing, deploying and decommissioning such facilities. Research in this area will include examining and reviewing turbine access systems, and escape and casualty rescue.
- Education – critical for delivering safety, and requiring well-trained people equipped with skills and knowledge needed to carry out their roles safely.
- Environment – the natural environment of the land and seas in which wind resources will be developed, and the physical environment that dictates the conditions for which machines are designed and built. Research will involve collecting and understanding relevant climatic, meteorological, oceanic and geotechnical data, to inform both the technological and policy dimensions of new offshore wind energy developments. Better knowledge will significantly reduce development risks and financial uncertainty.

The emergence and recognition of such common themes points also to issues that are likely to be of relevance for regulators in New Zealand. For example, any exploitation of New Zealand's vast offshore wind energy potential will need to take these common themes into consideration.

Tidal Wave Energy

The global tidal wave energy potential is estimated to be about 2.5-3.0 TW, about 1 TW being available at comparably shallow waters. Estimates of potential electricity generation vary between 200-400 TWh[146]. An independent market assessment indicates that tidal wave energy could contribute up 12% of world electricity consumption (based on 2009 data) and is comparable to the amount of electricity currently produced world-wide by large-scale hydroelectric projects[147].

Tidal wave energy is still in very early stages of development, with the technology still a long way off being able to compete seriously with fossil-fuel or other renewable energy sources. Apart from a few small plants being developed commercially, most of the plants built around the world are pilot or demonstration plants. In perhaps a decade or so of further technology development, tidal wave energy could reach large-scale application as a recognised and valued part of the clean technology portfolio.

Tidal wave energy works by converting the energy generated by tidal waves into electricity, using:

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[146] IEA-OES Annual Report, 2009.

[147] http://www.altprofits.com/ref/report/ocean/ocean.html

- Tidal barrages – built near the coast where water is collected during the high tide period, and released through a turbine back to the sea during the low tide period. This requires large capital investment and typically involves long construction times, although subsequent generation costs remain very low and output is stable and predictable. The first commercial scale tidal barrage system was constructed at La Rance (France) in 1967, with a capacity of 240 MW, and it remains the world's largest capacity tidal barrage. More recently, this technology is finding its way into new areas, as illustrated by recently announced plans to build a 50 MW system in Gujarat (India)[148].
- Tidal turbines – a new form of tidal wave technology, with turbines arranged in rows underwater where there are favourable wave currents, and energy transported to land using massive cables. (NB. This is the technology proposed by Crest Energy[149] for their Kaipara Harbour tidal energy development, with a capacity of 200 MW). Several private companies (e.g. Ocean Power Technologies[150]) are pioneering this technology. Most of the research on this type of tidal energy technology is taking place in Europe, with almost 100 companies involved.

Given the potential scale of tidal and wave energy relative to the current state of deployment, the opportunities for investment are huge. The United Kingdom is leading the development efforts, followed by the United States. Numerous research efforts are currently being developed in various countries, including the European Marine Energy Centre in the United Kingdom[151], the Wave Energy Research Team at the University of Limerick in Ireland[152] and the National Marine Renewable Energy Centre at the Oregon State University in the United States[153].

Energy Efficiency

Transport

Research towards more energy efficient transport systems is typically focusing on helping industry introduce advanced, low-emission, economically competitive vehicles and fuels into the marketplace. Key areas being explored include[154]:

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[148] http://www.bbc.co.uk/news/science-environment-12215065

[149] http://www.crest-energy.com/

[150] http://www.oceanpowertechnologies.com/

[151] http://www.emec.org.uk/

[152] http://www.ul.ie/wert/wave_energy_tech.htm

[153] http://nnmrec.oregonstate.edu/

[154] http://www.eagar.eu/docs/Aachen_workshop_041010_ERTRAC.pdf

- Greater energy efficiency of engines, vehicles and transport systems;
- Greater use of alternative transport modes, especially in urban areas;
- Greater use of services and solutions enabled by ICT;
- Substantially increasing the share of renewables in road transport;
- Greater use of biofuels in road fuels; and
- Greater use of renewables in electricity generation (i.e. for use in battery-electric automobiles).

Construction

Energy efficiency for building and construction is an active research area internationally. Energy efficient buildings can use 60-70% less energy than an average commercial building, with the savings achieved through a combination of improved building envelope design, efficient material, and energy-use technologies. In addition to reduced energy cost, such buildings may also generate energy through renewable sources and other smart technologies.

Key areas of energy efficiency research for building and construction include;

- Low-energy materials – containing recycled content, rapidly renewable products and/or locally sourced[155];
- On-site energy generation – integrating photo-voltaic energy capture technology[156];
- ICT-based management systems – e.g. for building automation and control[157];
- Low-energy alternatives to air-conditioning systems – e.g. using phase change materials such as paraffin[158]; and
- Building standards and codes –enhanced code mechanisms, creating room for higher standards but also greater flexibility for builders[159].

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[155] http://www1.eere.energy.gov/library/pdfs/47763.pdf

[156] http://www.nrel.gov/pv/building_integrated_pv.html

[157] http://www.projectsmagazine.eu.com/randd_projects/the_impact_of_ict_for_energy_efficient_buildings

[158] http://www.fraunhofer.de/en/research-topics/construction/microencapsulated.jsp

[159] http://www.scribd.com/doc/53706880/22/Energy-Efficiency-Building-Standards-in-Nordic-Countries