Chapter 7

The Bioeconomy of 2030

What is the bioeconomy of 2030 likely to look like? This chapter describes a "probable" bioeconomy in 2030 and develops two fictional scenarios that explore the interaction of different factors on possible futures. The "probable" bioeconomy builds on the types of products that are likely to reach the market by 2015. Within the OECD region, biotechnology could contribute to 2.7% of GDP in 2030, with the largest economic contribution of biotechnology in industry and in primary production. The economic contribution of biotechnology could be even greater in developing countries, due to the importance of these two sectors to their economies.

The scenarios assume an increasingly multi-polar world, with no single country or region dominating world affairs. They include plausible events that could influence the emerging bioeconomy. The results highlight the importance of good governance, including international cooperation, and technological competitiveness in influencing the future. Complex scientific challenges and poorly designed regulations could reduce the ability of industrial biotechnologies to compete with other alternatives. For instance, rapid reductions in the cost of renewable electricity combined with technical breakthroughs in battery technology could result in electrical vehicles out-competing biofuel transport systems. Public attitudes could result in some biotechnologies not reaching their potential. An example is predictive and preventive medicine, where the advance of this technology could be limited by public resistance to poorly planned and intrusive healthcare systems.

Introduction

So far, this report has identified the types of biotechnological processes in use and the products on the market today (Chapter 3) and likely to appear by 2015 (Chapter 4). Chapter 5 looked at the role of regulation, intellectual property rights, and public attitudes in the emerging bioeconomy. Chapter 6 examined emerging business models that could solve some of the bottlenecks and take advantage of new opportunities.

This chapter goes further, using two methods to evaluate what the bioeconomy of 2030 might look like. The first method adopts a "business as usual" approach, identifying biotechnologies that could reach the market by 2030 and estimating the potential size of the bioeconomy. The second method uses scenario analysis to explore the factors that could lead to very different bioeconomies by 2030.

The probable bioeconomy in 2030

How likely are different biotechnologies to be commercially successful by 2030? Two key factors, identified through the scenario exercises described below, are the rate at which biotechnological research produces successful innovations, and changes to regulatory and institutional policies. For both factors, this estimate of the probable bioeconomy adopts a conservative perspective. First, the estimate assumes that long time periods are required to develop a discovery into a commercially viable application, as supported by the historical record for biotechnologies (see Chapter 1). Second, the estimate assumes that most changes to regulatory and institutional policies are likely to be adaptive. Policy changes that require deep or disruptive economic changes are much more difficult to implement and consequently less likely.

Table 7.1 lists (in no particular order) the types of biotechnologies that are likely to be available by 2030. For these biotechnologies, the probability of solving scientific and technological problems is high, they are likely to be commercially viable, and regulatory and institutional conditions are already supportive in several major markets. Many of these biotechnologies are already commercially viable in some form or close to commercialisation.

Table 7.1. **Biotechnologies with a high probability of reaching the market by 2030**

Primary production	Health	Industry
Widespread use of MAS in plant, livestock, fish and shellfish breeding.	Many new pharmaceuticals and vaccines, based in part on biotechnological knowledge, receiving marketing approval each year.	Improved enzymes for a growing range of applications in the chemical sector.
GM varieties of major crops and trees with improved starch, oil, and lignin content to improve industrial processing and conversion yields.	Greater use of pharmacogenetics in clinical trials and in prescribing practice, with a fall in the percentage of patients eligible for treatment with a given therapeutic.	Improved micro-organisms that can produce an increasing number of chemical products in one step, some of which build on genes identified through bioprospecting.
GM plants and animals for producing pharmaceuticals and other valuable compounds.	Improved safety and efficacy of therapeutic treatments due to linking pharmacogenetic data, prescribing data, and long-term health outcomes.	Biosensors for real-time monitoring of environmental pollutants and biometrics for identifying people.
Improved varieties of major food and feed crops with higher yield, pest resistance and stress tolerance developed through GM, MAS, intragenics or cisgenesis.	Extensive screening for multiple genetic risk factors for common diseases such as arthritis where genetics is a contributing cause.	High energy-density biofuels produced from sugar cane and cellulosic sources of biomass.
More diagnostics for genetic traits and diseases of livestock, fish and shellfish.	Improved drug delivery systems from convergence between biotechnology and nanotechnology.	Greater market share for biomaterials such as bioplastics, especially in niche areas where they provide some advantage.
Cloning of high-value animal breeding stock.	New nutraceuticals, some of which will be produced by GM micro-organisms and others from plant or marine extracts.	
Major staple crops of developing countries enhanced with vitamins or trace nutrients, using GM technology.	Low-cost genetic testing of risk factors for chronic diseases such as arthritis, Type II diabetes, heart disease, and some cancers.	
	Regenerative medicine provides better management of diabetes and replacement or repair of some types of damaged tissue.	

Primary production

In primary production, biotechnology is already widely used to develop diagnostics for plant and animal diseases and to develop new varieties of trees, crop plants, livestock animals and aquaculture species with valuable traits. Applications to breeding include not only GM, but also many other biotechnologies such as gene shuffling, intragenics and marker assisted selection (MAS). The use of biotechnology in primary production is therefore likely to be pervasive by 2030 for the production of plant and animal food sources and for plant sources of feed and fibre. The separation

of agriculture into biotechnology and non-biotechnology disciplines will be obsolete, due to the rapid adoption of biotechnology to develop better diagnostics and improved varieties of farmed plants and animals.

Three uses of biotechnology for primary production face economic or social barriers: animal cloning, the use of GM technology for small market crops, and the use of GM to develop functional foods. By 2030, the most probable use of animal cloning is to produce high-value animal breeding stock and compounds such as pharmaceuticals. The main barrier to greater use of cloning is likely to be public opposition to cloned meat. The application of GM to small market crops does not face large technical barriers, but it could be constrained by regulatory costs and an ongoing focus by the small number of multinational seed firms on large market crops. GM functional foods for developed countries also face cost constraints compared to cheaper alternatives such as fortifying food. The most probable use of biotechnology for functional foods is in developing countries, where breeding programmes for major staple crops could use biotechnology to increase levels of essential minerals and vitamins.

Health

In health, almost all research to develop or apply new diagnostics and pharmaceuticals will use biotechnology, for instance to identify drug targets, improve drug delivery, or tailor prescribing practices to the genetic characteristics of patients. The exception will be generic drugs that were developed before 2015, although even here prescribing practices will be increasingly influenced by pharmacogenetics. Testing for serious genetic diseases will be widespread and inexpensive. Testing for genetic profiles that increase the risk of chronic diseases such as arthritis, Type II diabetes, heart disease, and some cancers will also be inexpensive, but the use of these tests in medical practice could be restricted to higher-risk older populations or to individuals that already show other risk factors for these diseases.

Both pharmacogenetics and analysis of linked medical records will improve the safety and efficacy of therapeutic treatments. The latter will allow researchers to link prescriptions, behavioural factors and genetic data to long-term health outcomes. This will significantly improve public health by identifying adverse drug reactions, unwanted drug interactions, and other factors that both negatively and positively influence health outcomes. It will also reduce the potential market for therapies that are only effective or safe for specific sub-groups, and it could lead to more drug withdrawals after market approval. Several hundred genetic biomarkers could be validated for use in drug prescribing.

The promise of both regenerative medicine and predictive and preventive medicine will only be partly realised. Although many of the necessary technologies and research discoveries for these two biotechnologies are under development, there are still many technical, economic and social challenges that need to be solved. Nonetheless, several types of regenerative medicine will be available by 2030, such as to treat diabetes or to repair damaged tissue. The replacement of complex organs such as the heart, lung or liver is likely to lie further off in the future.

Industry

The use of biotechnological processes in industry is increasing rapidly and will likely continue to increase up to 2030, but there are several possible outcomes. The future use of biotechnology to produce bulk chemicals, polymers and fuel is uncertain, partly because economic competitiveness will depend on government investment to create markets. Industrial biotechnology will moreover need to compete with alternative technologies, from other technological fields. As an example, biofuels will compete with alternative sustainable sources of power, including wave, geothermal, wind, solar and nuclear energy, and with fossil fuels combined with carbon capture and storage. Biofuels have an inherent advantage for transport applications because they are the only renewable source of liquid fuel and because some types of biofuels do not require substantial changes to existing transportation infrastructures. Nevertheless, technical breakthroughs in battery technology and in the generation of renewable electricity could give the edge to electric vehicles powered by solar energy or other sources of electricity.

The most probable industrial uses of biotechnology in 2030 are to produce enzymes for a range of industrial processes; one-step synthesis of high-value chemicals and plastics using micro-organisms in bioreactors; and the production of high energy-density biofuels from sugar cane and cellulosic crops. Large-scale commercial production of bulk chemicals or biofuels from micro-organisms or algae, without the use of biomass, is less certain by 2030, due to considerable technical difficulties in scaling up production to commercially competitive levels.

Integration

The level of integration of the bioeconomy in 2030 will be influenced by the competitiveness of biotechnological solutions compared to other technologies. A major unknown is the future of biomass production, cultivation and use. If biomass provides an economically and environmentally sustainable feedstock for chemical and fuel production,

there will be extensive integration between primary production and industrial biotechnology. Conversely, if other technologies – including synthetic biology – prove superior, the level of integration will be reduced. It is highly likely that there will be some degree of integration, however, as biorefineries should be competitive in humid tropical and sub-tropical regions with high rates of plant production, which includes the south-eastern United States.

In 2030 the bioeconomy will be integrated with alternative sustainable technologies for reducing resource constraints and environmental problems, as part of a global shift towards greater social and economic sustainability. Life cycle analysis will be widely used to identify the most environmentally sustainable products and methods for manufacturing products. Some chemicals might be produced using petroleum or natural gas feedstocks, while others might be more efficiently produced using biomass. Energy production will be based on a mix of renewables, with the specific mix dependent on local resource assets.

A shift to developing countries

The increase in the global population to 8.3 billion by 2030 will increase demand for food, feed, energy, fertiliser and clean water. A large share of the production and consumption of biotechnological industrial and primary products by 2030 will be in developing countries such as Brazil, India, China and South Africa, due to growing populations and incomes.

Several of these countries are also likely to be world centres for biotechnological research, based on an ample supply of highly skilled researchers, particularly in China. The increasing role of developing countries in biotechnology will influence the location of skilled human resources, R&D, markets, competition and trade.

For all applications of biotechnology, firms will increasingly adopt a global strategy to take advantage of research capabilities, technological advances and markets in both developed and developing countries.

The economic impact of the bioeconomy

An estimate of the impact of biotechnology in OECD countries or on the global economy in 2030 would require trend data for each class of biotechnology products and processes as well as estimates of how the product mix might change over time – for example, by how much will the relative size of the market for biopolymers increase in 2030 compared to the market for basic food staples? This task would require a report of its own.

However, a rough estimate of the future economic impact of the bioeconomy can be made by assuming that the economic share of each major application will remain approximately equal to what is observed today**.** For example, primary production accounted for 1.77% of total gross value added (GVA) in the European Union in 2005 and is assumed to account for a similar share of GVA in 2030.

A first step in this exercise is given in Table 7.2, which shows the maximum possible economic impact of biotechnology in the three main application fields. This would be achieved if *all* economic activities in the three key sectors involved biotechnology: pharmaceutical manufacturing (the main health application), primary production, and industrial sectors where biotechnology can be applied. Under this assumption, the maximum contribution of biotechnology to gross value added (GVA) in the EU-25 and the United States would be 5.6% and 5.8%, respectively. These sectors account for over 4% of employment in the EU-25 and 2.5% in the United States.

Of course, biotechnology is unlikely to contribute to this level of economic activity by 2030, although it may approach this limit at a later date**.** Many industrial processes will continue to rely on existing technologies in 2030, with biotechnology possibly contributing to 35% of all chemical production in 2030 within the OECD area.[1] Biotechnology will contribute to the development and production of almost all new pharmaceuticals in 2030, but generics that predate the biotechnology revolution will account for part of the pharmaceutical market. In 2005, generics accounted for between 10% and 40% of the pharmaceutical markets in European countries (Perry, 2006). The contribution of non-biotechnological generics should decline over time, so a generous estimate is that they would account for 20% of pharmaceutical GVA in 2030, with biotechnology accounting for 80%. In primary production, biotechnology will not be widely used in boreal forests, but it could contribute to half of agricultural production and almost all of aquaculture and plantation forestry, for a total contribution of approximately 50% of primary production output. Given these shares, a rough estimate is that the potential contribution of biotechnology to GVA by sector in the OECD plus a few other European countries, based on current shares and GVA levels by application, would total USD 1 062 trillion: USD 259 billion in health, USD 381 billion in primary production, and USD 422 billion in industry. This equals approximately 2.7% of total GVA in these countries.[2]

Table 7.2. **Maximum potential contribution of biotechnology to gross value added and employment**

	GDP[1] (USD billions)	Share of gross value added (%)			Total employment (thousands)[6]	Share of total employment (%)		
		(Health) Pharmaceuticals[2]	Primary production[3]	Industrial sectors where biotech has some application[4,5]		Pharmaceuticals[2]	Primary production[3]	Industrial sectors where biotech has some application[4,5]
EU-25	16 379	0.66	1.77	3.13	171 247	0.31	1.87	1.96
United States	13 790	1.24	1.83	2.71	141 216	0.23	1.04	1.25
Australia	890	0.27	3.08	3.83	8 741	0.13	2.06	1.41
Canada	1 406	0.36	2.21	3.99	15 314	0.19	2.65	-
Iceland	20	-	9.34	1.52	0.159	-	6.88	-
Japan	5 103	0.62	1.34	1.94	52 935	0.21	0.82	1.73
Korea	982	-	3.78	4.91	21 557	-	8.82	-
Mexico	886	0.73	3.79	6.23	-	-	-	-
New Zealand	124	-	9.19	-	1 443	-	0.65	-
Norway	369	0.23	1.46	-	2 310	-	3.60	-
Switzerland	414	-	1.36	-	-	-	-	-

Sources:

1. 2007 GDP in official exchange rates from the CIA Factbook.

2. EUKLEMS Project Database for the EU-25, the United States, Australia, and Japan, data from 2005; OECD Structural Analysis Database (STAN) for all other countries for 2004 except Canada (2002 for value added and 2003 for employment), Mexico (2003 for value added) and Norway (2002 for value added). The two databases are not fully comparable. There are no data for Turkey.

3. EUKLEMS Project Database for the EU-25, the United States, Australia, and Japan, data from 2005; OECD STAN for all other countries for 2003 except Canada and New Zealand (2001 for value added and 2003 for employment), Iceland (2002 for value added and 2003 for employment), and Switzerland (2002 for value added). The two databases are not fully comparable.

4. EUKLEMS Project Database for the EU-25, the United States, Australia, and Japan, data from 2005; OECD STAN for all other countries for 2004 except Canada (2001), Iceland (2002), and Japan, Korea, and Mexico (2003). The two databases are not fully comparable.

5. Relevant sectors with biotech applications: metal mining (1314), textiles (17), pulp & paper (21), chemicals excluding pharmaceuticals (24) and instruments (3345). The NACE code for each sector is given in parentheses. Data not available for Canada (instruments), Iceland (mining), and Mexico (textiles and pulp & paper).

6. EUKLEMS Project Database for the EU-25, the United States, Australia, and Japan, data from 2005; OECD STAN for all other countries, data from 2003 except Australia (2001). The two databases are not fully comparable.

These figures underestimate the potential for biotechnology in 2030, as they exclude biofuels, new applications that are not currently imaginable, and impacts that are difficult to measure in monetary terms. Such impacts include the effect of health biotechnology on the length and quality of life, and the environmental benefits of agricultural and industrial biotechnologies. Furthermore, they do not take into account increases in the GVA of each application – such as an increase in agricultural output in response to increasing demand for biomass as an industrial feedstock.

A striking implication of these rough estimates is that the economic contribution of biotechnology is potentially greatest in industrial applications, with 39% of the total potential GVA from biotechnology, followed by primary production with 36% of the total and health applications at 25% of the total. This estimate conflicts sharply with an OECD estimate of the distribution of R&D expenditures by businesses in 2003, as shown in Table 7.3. The lion's share of private sector R&D investment, 87%, went to health applications in 2003, with only 2% of biotechnology R&D expenditures spent on industrial applications.

Table 7.3. **Current R&D expenditures versus future markets for biotechnology by application**

	Share of total OECD business expenditures on biotech R&D in 2003	Estimated potential share of total biotechnology gross value added (GVA)[1] in the OECD area[2] for 2030
Health	87%	25%
Primary production	4%	36%
Industry	2%	39%
Other	7%	-
	100%	100%

1. See Table 7.2 and the accompanying text for the estimated potential share of biotech GVA by application.

2. OECD member countries plus several EU-25 countries that are not members of the OECD. Due to a lack of data, Turkey is not included.

Source: OECD (2006) for the distribution of biotech R&D expenditures.

These results suggest that private sector investments in biotechnology R&D are not in line with the potential market opportunities for biotechnology by application. This could partly reflect higher R&D productivity in primary production and industrial biotechnology compared to health biotechnology, but a lack of incentives, supporting regulations, skilled researchers, or complementary investment in public sector R&D could also play a role. A change in private sector priorities could already be

under way, however, as shown by a recent increase in investment in clean energy (Dellenbach, 2008).

Biotechnology could account for an even higher share of GDP in developing countries, due to the greater importance to GDP of primary and industrial production compared to OECD countries. In contrast, the share of GDP from the use of biotechnology to develop and manufacture pharmaceuticals and medical devices is likely to be greater in developed countries, due to the concentration of advanced research capabilities and markets in the OECD area. Most new health technologies will also be too expensive for much of the world's population. This will limit the benefits of many health biotechnology products in 2030 to a population of 1 billion in the developed countries, where per capita incomes are sufficient, and possibly another 500 million to 1 billion affluent individuals in developing countries.

Scenarios for the bioeconomy of 2030

The probable bioeconomy of 2030 that is described above is based on "business as usual" conditions. Yet, the bioeconomy of 2030 could vary substantially from this baseline, depending on unforeseeable events plus the interaction of technological, economic and political choices.

Two scenarios, included in Annex 7.A1 to this chapter, investigate how different drivers and events *might* shape the future of the bioeconomy, both within OECD countries and worldwide. It should be noted that scenarios are not capable of either predicting the future or creating a consensus over the most likely outcomes. Unlike the estimates in Chapter 2 on the global population, age structure and energy consumption in 2030, they are not extrapolations and consequently of no value for long-term economic or technological planning. Instead, the scenarios serve as a tool for thinking through the future implications of a range of political and private decisions.

The scenario exercise began with the construction of six scenarios: two each for primary production, industrial, and health biotechnology.[3] An analysis of these six scenarios showed that the two key influences on the future bioeconomy are the successful commercialisation of biotechnological products and processes (dependent on advances in science and technology and on the competitiveness of biotechnology compared to other technologies) and the quality of governance, defined as the system of regulations and policies that influence the development and use of biotechnology. The six scenarios were combined into the two composite scenarios provided in the annex: "Muddling Through" and "Uneven Development". In contrast to many scenario exercises, which tend to

provide either consistently positive or consistently negative outcomes,[4] these two scenarios include a mix of both positive and negative outcomes. The "Muddling Through" scenario, however, leads to more positive outcomes than the "Uneven Development" scenario.

Both scenarios build on the estimates in Chapter 2 of the drivers of the bioeconomy and the short-term predictions in Chapter 4 on the types of biotechnologies that should reach the market by 2015. They assume an increasingly multi-polar world, with no single country or region dominating world affairs (Zoellick, 2008), and include plausible natural and political events that could influence the bioeconomy. In addition to the possible effects of the global financial crisis of 2007-2010 on the bioeconomy, these plausible events include environmental degradation, drought and poor weather, disease, and a case of bioterrorism. The scenarios do not include highly unlikely events such as a global pandemic resulting in many hundreds of millions of deaths. The reader is reminded that these two scenarios are entirely fictitious. They are written in the past tense as "histories" viewed from a 2030 perspective. The citations in the full scenarios are only provided to support the plausibility of some of the fictitious events.

A short summary of each scenario is given below, along with a discussion of the relevant policy lessons that can be drawn from them.

Scenario 1: "Muddling Through"

Between 2009 and 2013 research and business investment in biotechnological applications for primary production and industry continued to grow, in part due to an expected return to high commodity prices after the global financial crisis of 2007-10. In addition, governments supported biotechnology investment and research as part of economic growth initiatives. However, it was apparent after 2010 that the era of abundant cheap capital for investment in high-risk technology firms had ended. This particularly affected pharmaceutical start-ups, with investment shifting to less risky areas with shorter-term payoffs, such as medical devices, diagnostics, bioenergy, and agricultural biotechnology. The decline in cheap capital partly supported a search for new business models that could reduce costs through sharing knowledge.

Investment in predictive and preventive medicine continued, but the concept faced serious barriers from rising costs, with a growing public debate on where healthcare dollars should go – to low-cost lifestyle changes or to high-cost medical interventions. The former was partly supported by the response to an influenza pandemic in 2014, where public health actions such as quarantines and travel restrictions were more effective than new

antiviral drugs. The influenza crisis also strengthened the ability of international institutions such as the WHO to manage and address health threats. There was some progress in other regulatory conditions for health, such as an agreement between the Food and Drug Administration (FDA) in the United States and the European Medicines Agency on the validation of biomarkers. The FDA also introduced requirements for ongoing assessment of pharmaceuticals after market approval and the US government earmarked funds for clinical trials to compare the efficacy of different pharmaceuticals for treating a specific disease. Mid-sized public health jurisdictions developed comprehensive medical record systems that permitted researchers to investigate the long-term effects of pharmaceutical use and environmental factors on health outcomes. This research reinforced the benefits of a science-based versus "art-based" medical system, but success in changing doctor and patient behaviour was patchy.

Two consecutive years of extreme drought and high temperatures in the main grain growing regions of the world in 2016 and 2017 drove global grain supplies to a record low and prices to a record high. Serious starvation in the poorer parts of the world was narrowly avoided through the actions of the United Nations to obtain global agreement to restrict the use of grain as animal feed. The experience proved the worth of drought-resistant GM crops, causing Europe to end its GM moratorium. It also served as a wake-up call to take climate change seriously, leading to global agreement to phase in carbon taxes that were high enough to lead to notable reductions in GHG emissions. This led to increased energy conservation as well as an investment boom in low-carbon energy, including biofuels.

In 2019, several factors conspired to shift the incentive and funding systems for health research from patents and market pricing of patented drugs to a global prize-based system, where patents expired once market approval was obtained. All new drugs were therefore produced at generic prices. Firms were rewarded for drug discovery by financial "prizes" that varied with the health benefits of each drug. The pharmaceutical industry accepted the new system because it offered a solution to the long-term decline in profits due to shrinking market sizes for individual drugs (in part from the use of pharmacogenetics) and because an international levy system based on national per capita GDP created a large prize pool that could amply compensate risky investments in health research. National governments accepted the new system because it reduced healthcare costs, particularly in middle- and low-income countries. The prize system also increased investment in research for medical devices and regenerative medicine. Investment in the latter had suffered under the patent system because patents could not adequately protect therapies based on stem cells and tissue engineering.

The years between 2025 and 2030 marked the consolidation of the bioeconomy, with widespread adoption of biotechnological techniques in primary production. There were a few failures, such as the release of enormous reservoirs of carbon from the conversion of savannah and rainforest in South America and Africa to cropland. This was due to a lack of international agreement on life cycle standards for agricultural products, biochemicals and high-density biofuels. The latter were produced from sugar cane or fast-growing grasses and trees, particularly in tropical and sub-tropical regions. Biofuels from algae could have reduced the need for vast areas of new cropland, but technical problems delayed this option. The cost of producing biofuels from algae only began to become competitive towards 2030, but its future is unsure, due to ongoing competition from alternative sources of renewable energy.

The focus of healthcare research had partly shifted from pharmaceuticals to regenerative medicine, diagnostics and surgical techniques. Research in predictive and preventive medicine had led to many successes in the ability to prevent or delay some types of cancer. Genetic screening of embryos for inherited diseases and high risks for other serious diseases was common. However, the general public resisted predictive testing on children and adults when there were no effective therapies to treat the disease, if it developed. Under these conditions, predictive testing created more anxiety and misery than good. Medical practice was both increasingly automated and personalised, with treatment regimes based on software that analysed genetic and other diagnostic test results, medical histories, and behavioural and environmental data. The ability of doctors to ignore best practice treatment protocols had declined, due to greater enforcement in managed healthcare systems.

Policy relevance of the "Muddling Through" scenario

A combination of good governance and the high technological competitiveness of biotechnology across a range of applications resulted in the beneficial outcomes outlined above. Good international governance was promoted by positive co-operative experiences, such as a co-ordinated response to a major influenza crisis. That helped countries reach agreement in later years over other important issues such as food shortages and climate change. The trust that developed also facilitated international co-operation on a new incentive structure for healthcare applications. Contentious issues remained, however, and global consensus was still a challenge that required compromise by all actors.

Serious crises can create a window of opportunity for governments to implement disruptive or radical change. For instance, in this scenario, a co-

ordinated approach to climate change was only introduced after a major scare of global food shortages. An uncoordinated and poorly governed approach (not explored in this scenario), where each country pursues its own interests independently, could have been disastrous, with increasing trade frictions over scarce resources and rapid climate change.

Biotechnology thrived in this scenario where it was technologically competitive, although in some cases, such as for biofuels, supportive regulation played an important role. Economic factors also influenced competitiveness and a search for solutions. The decline in the profitability of the pharmaceutical sector created an opportunity to put in place a new incentive structure for health research. These changes supported greater investment in technologies, such as regenerative medicine, that provided a higher socioeconomic return. Several promising technologies, exemplified in the scenario by predictive and preventive medicine and algal biofuels, were less successful than hoped due to complex scientific challenges. Algal biofuels also faced continued competition from alternative sources of clean energy, with no clear technical winner at the end of the scenario. In the case of preventive and predictive medicine, public resistance to intrusive healthcare limited its advance.

Scenario 2: "Uneven Development"

Between 2009 and 2014, agricultural biotechnology, controlled by five major firms, continued to build on past successes, with a steady stream of improved varieties of GM maize, wheat, rice and soybeans. Europe did not permit GM crops, but biofuel production in both the United States and Europe thrived. Mandates on the biofuel content of transport fuels favoured existing investments in crop-based biofuel production over cellulosic biofuels. In combination with technical difficulties, low subsidies for cellulosic biofuel led to a fall in investment in this technology, with green investors shifting towards solar and geothermal energy sources. Pressure from NGOs led to an end to all biofuel subsidies in 2014 in Europe.

In health, two of the world's largest pharmaceutical firms, an ICT firm and a private healthcare provider in the United States formed a joint venture to take advantage of the FDA's requirements for compulsory post-marketing follow-up and the use of pharmacogenetic information in clinical trials. The healthcare provider offered the pharmaceutical firms access to its members and its extensive medical database system in return for reduced drug prices.

No agreement had been reached internationally on GHGs. Interest in climate change had declined markedly because temperatures had increased very little since 2007. Climate scientists had predicted that a long cycle in

the earth's orbit would only create a temporary delay in climate change for a decade, but their warnings were ignored.

In September 2016 terrorists released a synthetic bacteria in London that caused severe intestinal pain in thousands of people. No one died, but the potential for terrorists to create a lethal bacteria or virus sent shock waves throughout the OECD area. Governments immediately shifted their priorities towards domestic security, introducing severe security restrictions on research into both synthetic life forms and GM research. The high cost of meeting these restrictions caused many industrial and agricultural firms to abandon research projects in these fields. They also found it increasingly difficult to retain scientific staff who left to take up higher-paid positions in biosecurity research. Security concerns prompted OECD governments to promote conservation and speed up the implementation of alternative energy sources to imported fossil fuels, including the construction of nuclear power plants. In North America, GHG production continued to increase.

Biosecurity research had several beneficial effects. It resulted in cheap diagnostic arrays for animal, plant and human pests and diseases. Doctors could quickly determine if cold symptoms were caused by viruses or bacteria, reducing overprescribing of antibiotics and consequently the development of resistant strains of bacteria. Global databanks of plant and animal DNA, maintained as part of biosecurity, were used in the 2020s to prevent illegal trade in biomaterials.

The health sector was largely protected from the problems affecting agricultural and industrial biotechnology, due to more competitive salaries and US funding of research to quickly identify and treat new pathogens. The joint venture for health was shut down in 2020 and replaced by a merger between the partners, dominated by the ICT firm and the healthcare provider. The new business model was called a Networked Health Provider (NHP). The merger was driven by conflicts between the partners over the use of expensive drugs that were not particularly innovative and the unwillingness of the two pharmaceutical partners to move into regenerative medicine, which threatened some of their markets. The new firm was able to assemble new technology, build new types of expertise, and surmount regulatory barriers to innovation. The NHP model became very profitable, largely on the basis of adopting new medical devices and regenerative therapies, and was copied in India and China.

The fact that the main route to market for healthcare products was increasingly mediated by NHPs meant that small firms could develop a much wider range of healthcare products. Drug development no longer dominated health biotechnology, with almost half of private research invested in diagnostics and regenerative medicine.

The period between 2022 and 2030 was marked by a partial recovery in the use of biotechnology in primary production and industry. Brazil and a few other non-OECD countries had developed economically competitive biorefineries for high energy-density biofuels and for bioplastics by 2025, originally building on the expertise of European enzyme firms that moved part of their operations overseas to escape European and American restrictions on research.

Concern over GHGs and climate change grew into a serious global issue by 2027, due to seven consecutive years of accelerated climate change. This renewed interest in using GM and other biotechnologies to develop stress-resistant crop varieties. China and India were first movers in this area. Both industrial and agricultural firms lobbied OECD governments to relax some of the restrictions on the use of biotechnology.

The major success of the NHP health model created growing unease over the development of a highly visible two-tier healthcare system, with NHP members that could afford higher health premiums benefiting from better healthcare than individuals served by other healthcare providers. European and other countries with public healthcare systems were slow to adopt the NHP model and were therefore less successful in introducing an integrated system for providing healthcare. They also had to purchase many new therapies from NHPs at high prices. In response to a growing political debate over NHPs, several countries with publicly funded healthcare systems were threatening in 2030 to invoke the opt-out clauses of the agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPs) in order to produce patented therapies at low cost.

Policy relevance of the "Uneven Development" scenario

Some of the problems described in this scenario are due to variations in the technological competitiveness of biotechnology, often exacerbated by poor political decisions such as insufficient support for promising technologies. Although the security measures introduced as a result of the bioterrorist attacks resulted in several beneficial innovations, they also stifled growth in agricultural and industrial biotechnology. The situation was made worse by the unintended effects of higher salaries in biosecurity. Carefully designed systemic policies to support both biosecurity and agricultural and industrial biotechnology could possibly have avoided some of these problems. Progress in health biotechnology was supported by a major organisational innovation that closely linked research into health therapies with the provision of health services. Yet the benefits were not widely shared. At the end of the scenario, growing tensions over access

could have led several countries to undermine the system of patent rights that provided the main incentive for investment in health research.

The scenario is further marked by the failure to respond to global problems such as the threat of climate change. Concern over the issue declined because of a decade with little increase in global temperatures. Recognition of the problem did not develop until late in the scenario, when climate change returned with a vengeance. The solutions were inadequate, addressing the symptoms of climate change rather than the cause. The main response was to develop crop varieties adapted to hotter and drier growing conditions, rather than reducing GHG production.

Conclusions

Biotechnology could contribute to approximately 2.7% of the gross value added of OECD countries in 2030 and perhaps more, depending on favourable technological developments and policies. Of possibly greater interest to policy, biotechnology can increase productivity and help address climate change, water stress, food scarcity, energy security, and disease. All of these challenges are included in the scenarios.

The descriptions in this chapter of the probable bioeconomy and the two scenarios of different futures show that many factors will influence the emerging bioeconomy. Some of the factors are fortuitous technological advances, both in biotechnology and in competing technologies. Other factors include the major challenges facing the world, such as food scarcity due to climate change and drought or disease pandemics among livestock.

Several of the events described in the scenarios create political crises that also open windows of opportunity. How governments react to financial crises, food scarcity or pandemics can shape the future development of the bioeconomy. The future is also influenced by international co-operation, especially with developing countries, and incentive structures for research and markets. Incentives influence the types of biotechnologies that are commercially viable and the distribution of its benefits. The structure of incentives can also support environmentally sustainable technologies over less benign alternatives – or *vice versa*.

Although the events described in the scenarios are completely fictitious, the lesson to be learned is the key role of good governance. This requires well-designed policies to support the current trajectory of the bioeconomy and flexible policies that can foresee and effectively respond to unpredictable crises. Policy options for the bioeconomy are examined in the following chapter.

Notes

1. The 35% estimate is obtained from linear extrapolation to 2030 of the USDA upper estimates of the biotechnology share of world chemical production in 2005, 2010, and 2025 (see Table 4.6 in Chapter 4). The lower USDA estimates would predict a 2030 biotechnology share of world chemical production of 27%. The upper estimate is used here for OECD countries, under the assumption that technical progress will be greater within the OECD countries than within developing countries.

2. These estimates are calculated from the data in Table 7.2 for each OECD country and assume that 80% of pharmaceutical production would be due to biotechnology, 50% of primary production, and 35% of industrial production in sectors where biotechnology has potential applications (see Note 5 to Table 7.2). Missing data, such as health GVA for New Zealand, are estimated from the nearest neighbour in terms of economic structure. Therefore, the GVA share for Japan is applied to Korea, Australian GVA shares to New Zealand, USGVA shares for pharmaceuticals to Switzerland, and EU GVA shares for industrial production to Switzerland and Norway.

3. Three reports develop the scenarios for health, primary production, and industry. See Tait *et al.*, 2008 for scenarios of health biotechnology; Murphy *et al.,* 2008 for scenarios of primary production biotechnology; and MacRae, 2007 for scenarios of industrial biotechnology. All scenarios can be downloaded from www.oecd.org/futures/bioeconomy.

4. Other scenarios of the bioeconomy that were evaluated for this report have end-dates between 2015 and 2056. See USDA, 2005; German Ministry of Education and Research, 2004; Bezold and Peck, 2005; EC, 2007; NZ MoRST, 2005; IBM, 2006; Neild and Pearson, 2005; WBCSD, 2000.

Annex 7.A1

Fictional Scenarios to 2030

Scenario 1 – Muddling Through

2010 to 2013: Gradual shifts

In 2010 investment in biotechnology research was dominated by health applications, which accounted for 85% of R&D expenditures. Agricultural biotechnology continued to build on past successes, with several new GM varieties of major crops reaching the market before 2012. These included improved product quality and drought tolerance traits for maize and soybeans. China began large-scale plantings of pest-resistant GM rice in 2011. Awareness of industrial biotechnology had increased as a result of the production of biofuels, which was a major market for GM enzymes.

The biofuels sector was experiencing biomass supply and market problems. Greater demand for biomass inputs had driven up the price of what was previously low-cost waste, while a glut in by-products from biofuel production drove down the price of what were previously profitable sources of income. The increased costs of biomass also increased the cost of producing biopolymers.

The substantial increase in prices for agricultural commodities and petroleum before 2008 had begun a gradual shift in the structure of the biotechnology industry. These commodity prices fell steeply after 2008 due to an increase in the supply of grains and a reduction in the growth of demand for petroleum due to the global financial crisis of 2007-2010, but prices still remained above the average of the 1990s. Investors expected the prices of agricultural commodities and petroleum to increase after 2010 due to a long-term increase in demand, leading to a sustained increase in investment in agricultural biotechnology and in energy. This was supported by government investment by several OECD and developing countries in R&D and infrastructure for primary production and industrial biotechnology, as part of economic growth initiatives in response to the global financial crisis. Venture capitalists invested in small firms working on cellulosic sources of biomass, such as low-lignin grasses. Large seed firms expanded their research programmes to develop crops with enhanced quality traits that would reduce biomass processing costs and increase conversion yields for biofuels and valuable chemicals. Research also increased in new and more efficient uses for plant and animal wastes for energy production.

The refusal of several European governments to permit plantings of GM grain crops faced increasing opposition from the European livestock industry, which was paying high prices to import GM feed from the United States and South America. However, European consumers

THE BIOECONOMY TO 2030: DESIGNING A POLICY AGENDA – ISBN-978-92-64-03853-0 © OECD 2009

remained hostile to GM. There was a general assumption by European policy analysts that public opinion would not change until consumers directly benefited from GM products, for instance from healthier GM foods. It was unlikely that consumers would benefit from a fall in prices, with almost all of the cost savings from GM going to seed firms and farmers. In contrast to the situation in Europe, Australian public opinion had turned strongly in favour of GM, due to fears over food security as a result of the long drought during the 2000s. By 2012 Australia had become a major grower of GM rapeseed, drought-resistant barley and other grains for animal feed.

The use of biotechnology in the health sector was rising rapidly. Biotechnologies such as RNA interference were widely used in drug discovery for both small- and large-molecule drugs. Over half of the clinical trials conducted included some pharmacogenetic data from patients; firms were seeking to reduce the prevalence of adverse drug reactions and experimented with identifying sub-groups of patients that responded well to therapy, particularly in cancer treatment. New diagnostics for genetic risk factors, targeting increasing numbers of genes, were continually appearing on the market, while the cost of genetic testing was falling steeply every year**.**

The concept of predictive and preventive medicine attracted increasing interest from pharmaceutical firms, venture capitalists and health policy analysts, but progress continued at a slow pace. The concept required patients who were very likely to develop a specific disease, due to a genetic predisposition or environmental factors, to take steps to prevent the disease from developing. Depending on the disease, this could require a change in lifestyle, diet, or medical treatment well before the development of symptoms. Diagnostic tests for risk factors for many chronic diseases – such as cancer, heart disease, arthritis and Type II diabetes – formed much of the predictive component of preventive medicine, but most of these tests could only detect relatively low risks. There were few predictive tests to determine if genetic or environmental factors were actually leading to specific diseases, rather than simply increasing theoretical risks. These predictive tests required validated blood protein and other markers that could detect a developing disease well before the appearance of symptoms.

Healthcare experts interested in predictive and preventive medicine were aware of the difficulties in getting patients to actively participate in changing their lifestyles. This problem was even greater when behavioural changes were suggested to patients long before the appearance of any symptoms. Research on smoking cessation programmes and dietary changes to control cholesterol levels had shown significant benefits (Kay-Tee *et al.*, 2008).This demonstrated that individuals, if sufficiently motivated, would alter their behaviour when faced with long-term risks. But the same research also showed how difficult it was to change long-term habits, and that any changes occurred slowly. Furthermore, research showed that people disliked prevention that required self-monitoring, as it increased anxiety and consequently reduced their quality of life (Gulliford, 2008).

Although the potential contribution of biotechnology to healthcare was widely appreciated, neither politicians, nor the CEOs of health product firms, nor public or private healthcare service managers knew how to solve the main problems of rising healthcare delivery costs, declining research productivity, and an apparent worsening of the cost/benefit ratio for new technologies. Many biopharmaceuticals, marketed at prices of over USD 50 000 per year, only

THE BIOECONOMY TO 2030: DESIGNING A POLICY AGENDA – ISBN-978-92-64-03853-0 © OECD 2009

made small improvements to the median survival of patients.[1] These results also intensified a debate over whether or not more public funding should go into low-cost lifestyle changes compared to high-cost medical interventions.

A major hurdle was how to pay for the identification and validation of over 2 000 potential biomarkers. To break this impasse, ten major pharmaceutical firms and non-profit research organisations had established a research consortium in the mid 2000s to identify and validate biomarkers. Additional members had joined over the years.

Validation required years of careful clinical trials and the ability to link long-term patient outcomes with biomarkers and treatments. In 2009 the European Medicines Agency (EMEA) and the Food and Drug Administration (FDA) in the United States agreed on mutually recognised standards for validating biomarkers, an essential step towards supporting research in this area. The standardisation built on earlier collaborative work between the EMEA and the FDA on harmonising the submission of pharmacogenetic data during clinical trials.

The FDA adopted a life cycle approach to evaluating the risk of pharmaceuticals that went well beyond market approval. It considerably strengthened its post-market follow-up requirements to identify long-term safety concerns and introduced mandatory registration of all clinical trial results. To complement these efforts, the National Institutes of Health (NIH) in the United States earmarked USD 500 million per year for comparative trials of different pharmaceuticals or other surgical treatments for the same medical condition.

2014 to 2025: The transition years

The Cambodian influenza pandemic of 2014 reinforced the need for a global public health surveillance system under the World Health Organization (WHO). Although the pandemic was the worst global flu outbreak since 1918, the experience gained ten years earlier during the SARS outbreak of 2003 proved invaluable in significantly limiting the scale of the pandemic to 20 million deaths worldwide – a much lower death rate than in 1918, when 40 million people died out of a much smaller global population (Smith, 2006). The use of antiviral medicines had only a limited effect on the pandemic. Most lives were saved due to public health actions such as quarantines and travel restrictions. The total economic costs of the pandemic were severe, estimated at 3% of global GDP. Many scientists were relieved that the pandemic had not occurred several years later. There had been talk of reducing the global health surveillance system as a way of reducing the costs of the overstretched United Nations budget.

As a result of the Cambodian flu pandemic, UN member countries agreed to a large increase in the UN's WHO surveillance budget and began discussions to establish a fund to support research into developing new antibiotics in order to address continued concerns over antibiotic-resistant strains of bacteria. Several years later, the United Nations also obtained earmarked funding to replace traditional poultry and livestock breeding methods in South East Asia with modern methods that substantially reduced contact between people and animals. The goal was to reduce the risk of transmission of zoonoses, such as influenza viruses, from animals to humans (Smith and Alvarez, 2008).

By 2013 it was widely recognised that the 25-year glut of cheap capital that had supported venture capitalist investment in long-term, high-risk technology projects had ended by 2010.[2]

THE BIOECONOMY TO 2030: DESIGNING A POLICY AGENDA – ISBN-978-92-64-03853-0 © OECD 2009

A major cause was increased opportunities for profitable short- and medium-term investments in developing countries, particularly after the global financial crisis of 2007-2010, which led to a large decline in petrodollars and Asian trade surplus funds invested in the United States. Investment in high technology followed higher rates of return in energy technology – part of a global boom in low-GHG energy sources – and in agricultural biotechnology due to high sustained prices for food and feed commodities. It became comparatively more difficult for small biotechnology firms in pharmaceuticals to raise capital. An increasing share of a dwindling supply of venture capital investments in health went to medical devices and diagnostics with shorter development times than pharmaceutical projects.

High prices for agricultural commodities had increased the rate of conversion of pasture and forest lands to crop production, particularly in South America, Indonesia, and parts of Africa with abundant rainfall (Bruinsma, 2003). The cost of growing grains in Africa was now competitive with world prices. By 2014 the "food versus fuel" debated had quieted down, with 15% of crop production going to biofuels; these used sugar cane and GM grain varieties that had been modified to reduce processing costs and increase fuel yields.

The success of the open source Biobrick Foundation in identifying genetic "building blocks" for chemical production raised interest in developing business models based on knowledge sharing and public/private research consortia. Several small industrial biotechnology firms were established in order to build on the results of the Biobrick movement. They developed customised micro-organisms that could produce valuable chemicals without the need for a large sequence of chemical synthesis steps. These organisms were sold to large chemical firms, a few of which had the capacity to develop designer micro-organisms in-house. Patent pooling and research consortia among public sector research institutes and small agricultural biotechnology firms in developing countries and in smaller developed economies such as New Zealand, Australia and Korea opened up new business models and attracted significant investment.

In 2014 the World Business Council on Sustainable Development held a conference to discuss an incentive system based on prizes for medical research (Love and Hubbard, 2007). Interest in a prize system had been gradually growing since a World Business Council meeting on the topic in 2001. The success of alternative business models such as patent pools and the Biobrick Foundation had also increased interest in looking for new types of incentive systems for research. Another factor in calling the conference was concern over falling market sizes for individual drugs from the increasing use of pharmacogenetics. The conference did not reach agreement over a prize incentive system. However, it did provide a forum for discussion between large and small pharmaceutical and medical device firms and public and private health service providers over incentives for health innovation. The WHO agreed to sponsor another meeting three years later in 2017.

Earlier enthusiasm for GM functional foods in developed countries waned, after market research established that the majority of consumers were unwilling to pay premium prices for nutrient-enriched staple foods. In contrast, smaller markets for specialty nutraceuticals boomed, in part due to public interest in preventive diets for cancer and other chronic diseases. An example was increased interest in producing Omega-3 fatty acids in GM algae. The main market for functional foods was in Africa, where agricultural research organisations used

Fictional Scenarios to 2030

biotechnology to develop cassava, maize and sorghum varieties with enhanced levels of essential minerals and vitamins.

Due to high feed prices for livestock, in 2014 all member states of the European Union accepted a proposal by the European Commission to allow farmers to grow crop varieties developed using intragenics,[3] but several major countries maintained their opposition to transgenic GM crops. The acceptance of intragenics improved conditions for seed firms as they could now use GM technology to transfer genes from wild strains of a species to elite cultivated varieties. In the same year, international agreement on the safety requirements for GM crops also reduced regulatory costs. This improved the ability of SMEs to develop gene constructs for small market crops such as vegetables.

The traceability systems developed at the turn of the century in response to the Bovine Spongiform Encephalopathy (BSE) crisis in the United Kingdom led to the development of advanced tracking systems for agricultural products. Microchips and accompanying scanners provided information on the health and movements of each animal from birth to death. These applications were used widely in developed countries and increasingly adopted in developing countries in order to maintain or access markets. In some cases, increased application of security and traceability measures was facilitated by World Trade Organization (WTO) agreements (such as those requiring export countries to maintain full records on livestock for export).

Biotech advances in food safety, such as microchip diagnostics that turned colour in the presence of bacterial contamination, allowed the WTO's *Sanitary and Phytosanitary Measures* and *Technical Barriers to Trade* agreements to continue to function effectively. These technologies were adopted by developing countries, such as China and Indonesia, that had experienced several severe cases of food contamination. Effective food safety technologies, improved tracking and tracing technology, and improved sanitation in food processing factories led to a drastic reduction in the number of contaminated food events.

The Malthusian years

Two consecutive years of extreme drought and high temperatures in the major grain growing regions of the world between 2016 and 2017, plus extreme weather events in many other regions, drove global supplies of the main food and feed crops of maize, rice, sorghum, soybeans and wheat to a record low. This caused an explosion in food prices, to a level that was painful even for developed countries. The problem was exacerbated by low global grain reserves for over a decade and the devastation of wheat crops in Europe and the Ukraine by a new strain of wheat rust fungus that originated in the Punjab region of Pakistan and India.

The "Malthusian years", as they were quickly called by journalists, fuelled further investment in agricultural biotechnology and in cellulosic fermentation for the production of biofuels. Average daily calories consumed in developed countries fell by 5%, followed by a dip in the percentage of the population that was obese and a decline in the number of new cases of Type II diabetes. Widespread starvation in poorer countries was only avoided by the actions of the United Nations to reach global agreement to curtail the use of grain and oilseeds for meat production and biofuels.

Fictional Scenarios to 2030

The Malthusian years also ended the European moratorium on GM crops. Opposition had been declining for years in the face of increasing awareness of the environmental benefits of GM in terms of reduced pesticide use and improved stress tolerance. Researchers had estimated that the Malthusian years would have been much worse without the widespread adoption of improved GM varieties of drought- and heat-tolerant maize and soybeans that had been introduced to the market in 2015 in the Americas, India and China.

Overwhelming data to support the theory of climate change had failed to convince developed and developing countries to take the phenomenon seriously, and previous agreements lacked enforcement mechanisms. GHG production in almost all major emitting countries had continued to increase every year. The experience of the Malthusian years spurred global acceptance of a binding agreement in 2019 to drastically increase carbon taxes, over ten years, to USD 500 per tonne. International Energy Agency (IEA) and OECD economists had estimated that a carbon price below this level would never encourage the sweeping social changes and private investments required to address climate change.

An immediate effect of the carbon tax was a jump in investment in energy conservation. Although conspicuous high-energy consumption had already become socially unacceptable, much waste still existed. The increase in carbon taxes also created an investment boom in low-carbon energy technologies.

Several large American and Brazilian agricultural and industrial firms invested in joint ventures to develop fast-growing perennial crops for cellulosic fermentation. Although the process remained more expensive than using starch plants such as maize, new technology was developed that could cheaply remove water from biomass, significantly decreasing transportation costs.

Another welcome technical breakthrough in Brazil resulted in the efficient large-scale production of high energy-density liquid biofuels from sugar cane. These biofuels had several important advantages over bioethanol. The energy density per litre was very close to that of gasoline, versus 69% for ethanol; they could be used in ordinary engines; and they did not attract water. This meant that they could be cheaply exported from Brazil in bulk tankers and shipped through existing pipelines.

Several publicly funded health jurisdictions covering populations of approximately 4-5 million people had established comprehensive medical records systems. These linked lifelong records on therapeutic treatments, genetics and environmental behaviours such as exercise, diet and housing with long-term health outcomes. The complexity of the informatics system for comprehensive healthcare favoured small to mid-sized health services. An early leader in the United States was the private health services firm Kaiser Permanente, with 9 million patients. Research by these health providers created a wealth of information on adverse drug reactions, the success of different health therapies, and both positive and negative interactions between different therapies. The early results increased medical knowledge of the most effective interventions for a range of chronic diseases. This helped to reinforce the benefits of a "science-based" medical system as opposed to an "art-based" system that left many treatment decisions to individual doctors. In these jurisdictions healthcare delivery was increasingly linked to the development of mandatory treatment protocols. However, success in

Fictional Scenarios to 2030

introducing evidence-based medicine was patchy. Doctors resisted restrictions on their ability to make decisions "best adapted to the individual". The public interpreted some of the guidelines as forcing patients to take the cheapest available option rather than the "best" option.

The profitability of the pharmaceutical sector was declining, due to the use of pharmacogenetics and evidence-based treatment regimes that had significantly reduced the market size for many drugs. Higher incomes in China and India had created double digit growth in pharmaceutical markets that partially compensated for the smaller markets in developed countries (Pharma Futures, 2007). China was already the world's seventh largest market for pharmaceuticals by 2010, while both China and India had the world's largest number of patients with diabetes and obesity before the Malthusian years. However, the affluent middle class in India and China was not large enough to fully compensate for the reduced size of individual drug markets in developed countries. In 2018, average incomes in India and China were approximately USD 1 800 and USD 3 500, respectively.[4] These lower median incomes meant that national health priorities focused on low-cost public health solutions.

High manufacturing costs for biopharmaceuticals required firms to charge high prices for this class of drugs. Synthetic biology provided opportunities for lower cost production, but still required expensive bioreactors. After 2014, production costs for most biopharmaceuticals fell by between 60% and 90%, with extensive production of biopharmaceuticals from GM plants raised in greenhouses. These were protected through state-of-the-art security systems to prevent counterfeit drug production based on the theft of GM seeds.

The Chinese and Indian governments had both established regulatory agencies modelled on the FDA rules. This was due to their strong interest in supporting internationally competitive domestic pharmaceutical firms that could sell products in the two major markets of the United States and the European Union. A Chinese biotech "triangle" with strengths in agricultural, pharmaceutical and industrial applications had developed in three coastal states (Zhejiang, Shanghai and Jiangsu), built around universities, agricultural field stations, manufacturing plants and medical hospitals in Shanghai, Nanjing and Hangzhou. Average per capita GDP in the three states exceeded USD 12 500 in 2015.[5] Comparatively high living standards, proximity to the Shanghai International Airport, a well-developed infrastructure, good schools, internationally competitive salaries in the biotech sector and attractive recreational areas nearby meant that the Chinese biotech triangle was successful in attracting both Chinese and non-Chinese star researchers working in OECD countries. A major advantage of the biotech triangle was expertise in platform technologies of relevance to each of the three main application fields.

The shift to MeDFAs

In 2018 a mid-sized biopharmaceutical firm obtained market permission in the United States and the European Union for Amespira, a biopharmaceutical for the most common type of lung cancer. The drug was the first significant breakthrough in lung cancer treatment, extending survival by a median of nine months compared to existing best practice treatment regimes.

Fictional Scenarios to 2030

However, the manufacturer priced Amespira at USD 200 000 per year, making it the most expensive drug in history other than a few drugs for very rare diseases. Many public and private insurers refused to pay for it. In the United States, the annual bill for Amespira to treat all new lung cancer cases was estimated at 10% of all expenditures on prescription drugs. Several Latin American and Asian countries used the public emergency and compulsory licensing provisions of TRIPs to manufacture biosimilar versions of Amespira for domestic use.

The case created intense public discussion within developed countries. Amespira was only covered by a few private healthcare plans for tertiary-level employees, who had very low smoking rates and hence low rates of lung cancer. Other patients had to either use their personal savings or do without. The glaring disparity in healthcare availability for a familiar disease flew in the face of people's sense of justice. The problem was particularly acute in Japan, due to the government's policy of not reimbursing "advanced" innovative new technologies. The manufacturer of Amespira mounted an unsuccessful public relations campaign insinuating that private individuals should cover the costs themselves, since no one could claim that they did not know that smoking caused lung cancer. The firm even offered to provide Amespira at a 75% discount for lifelong non-smokers.

The Amespira controversy gave political support to the case for using cash prizes as an incentive for medical innovation rather than patents. A number of other developments made the pharmaceutical sector much more receptive to the idea than it had been in 2014. The first was smaller drug markets and the near-disappearance of the blockbuster drug business model. One effect of these developments was a continual decline in the supply of funds to finance the next round of innovation. The second was the difficulty smaller biotech firms were encountering in raising venture capital. Third, large pharmaceutical firms were increasingly obtaining new drugs from small firms and earning a larger percentage of their revenues from generics. That meant that they had the expertise to manage complex royalty agreements and they were less reliant on profits from patented drugs. A fourth reason was associated with production problems. The increasing use of plants to produce complex pharmaceuticals had created several high-profile counterfeit cases, based on stolen seeds, which had reduced the revenue of a few major pharmaceutical firms.

A fifth reason was of particular interest to many American politicians. A cash prize system, with contributions based on national GDP, would end the free rider problem in drug development. Americans had complained for years that the high cost of drugs in the United States compared to other developed countries meant that Americans were subsidising medical innovation for the rest of the world. All proposals for the prize incentive system were based on a small levy on national GDP. This was designed to provide a prize pool equal to twice the global annual expenditures for R&D on pharmaceuticals and medical devices, or approximately USD 160 billion. The high potential payouts of this pool provided a sufficient profit incentive for long-term and risky investment. Even though the levy was tied to the UN World Development Index – so that wealthier countries paid a higher levy rate than poorer countries – the levy for the United States was 0.25% of GDP, which was one-third less than its private sector expenditures on medical R&D. American firms would also be able to compete on an equal basis with all other firms in the world for an annual fund four times greater than their current R&D levels.

Fictional Scenarios to 2030

The WHO, with the encouragement of many health NGOs, took responsibility for obtaining international agreement on the details of the Global Medical Discovery Finance Awards (MeDFA) Treaty. Firms quickly started to talk of one "MeDFA" as a unit of currency, worth USD 1 million. Many of the basic ideas had been worked out in the 2000s[6] and in the two international conferences in 2014 and 2017. The final agreement was reached comparatively rapidly in 2019, due to the much-improved international negotiating environment on health since the Cambodian flu pandemic of 2014.

The MeDFA Treaty solved problems of parallel imports, denial of access to medical innovations based on high costs, and the free rider problem. Patents were still permitted under the agreement, but once a medical innovation received marketing approval in a major market, the patent expired and the innovation could be produced by generic manufacturers. The production of biopharmaceuticals in plants made this particularly easy and drove down drug costs substantially. Patents were mainly used to apportion payouts among different firms that contributed to the innovation. The size of the award, paid out over ten years, included both a minimum amount and a sliding scale based on improvements in quality-adjusted life years (QALYs). A minimum award was essential to provide a research incentive for rare diseases. A certain percentage of the total annual award was also set aside for problems that were difficult to measure in QALYs, such as improved drug delivery systems, surveillance systems, and therapies for potential pandemics or for bioterrorism.

Building on the international discussions in 2014, the MeDFA Treaty also earmarked 3% of the annual prize for new antibiotics. Improved public health in the developing world, hospital sanitation, and restrictions on prescribing antibiotics in developed countries had contained the growing threat from antibiotic resistant bacteria – but the public health community was convinced that it was only a matter of time before antibiotic resistance led to an untreatable and serious global pandemic.

The main problem with the MeDFA system, familiar to many small biotech firms, was how to pay for research without a revenue stream. Large pharmaceutical firms largely stepped in as both financiers and co-ordinators. Since payouts were apportioned on the basis of contribution, there was a strong incentive to collaborate rather than getting involved in expensive and redundant races to be the first to bring an innovation to the market.

The MeDFA system caused several major changes in medical innovation. As it was open to firms in all countries participating in the treaty (which included almost all UN member states), it encouraged greater medical research outside the main centres of pharmaceutical innovation of the United States, Europe, Japan, China and India. Second, many of the awards for the first five years were given to small medical device firms, particularly those active in stem cells and tissue engineering. The previous patent system had failed many of these firms. The dominant method was to use stem cells derived from the patient. These cells were treated and cultured, with the resulting tissue surgically inserted into the patient. The process was labour-intensive, but more problematically it was easy to keep secret and hence avoid paying patent royalties. Patients from developed countries would seek low-cost royalty-free treatment in clinics in Brazil or India for new teeth, cartilage, or pancreas islet of Langerhans cells for diabetes. The incentive provided by MeDFA awards strongly encouraged more research on stem cells and

THE BIOECONOMY TO 2030: DESIGNING A POLICY AGENDA – ISBN-978-92-64-03853-0 © OECD 2009

tissue engineering. In contrast to a patent incentive system, MeDFAs also provided greater incentives to find a cure for chronic diseases.

2025 to 2030: Consolidation of the bioeconomy

Climate change, pollution, and population pressure on water and land resources reduced the quality of water supplies in many developing countries by 2030. This led to a higher incidence of some infectious diseases and greater dislocation of populations, which in turn led to an increase in TB. Global warming increased the possible geographical range of malaria, dengue fever and other diseases (Tong and Soskolne, 2007). Public health actions, including rigorous inspection of cargo to identify vector insects, prevented the spread of these diseases to developed countries. The cost of public health actions were kept low due to the development of automated non-invasive DNA probes to identify pathogens and vectors in people and cargo. The decline of new influenza epidemics from the automation of animal husbandry in South East Asia produced major health benefits.

Molecular biology advances such as viral coat protein technologies provided protection from viruses found in wheat, rice and potatoes. As a large percentage of the major and minor crops used in agriculture had known DNA profiles, some minor crops also benefited from virus reduction technologies. Additionally, the ability to transfer multiple genes through artificial chromosomes (Houben *et al.*, 2008) conferred resistance to both agronomic stresses such as heat, drought and salinity and to nematode, insect and fungal infections that had increased in frequency in the main global food crops (soybeans, maize, rice, wheat, and potatoes). As these resistance traits diverted plant resources from producing larger grains, beans or tubers, yields were enhanced when the resistance genes were turned "off". Farmers used automated biosensors and diagnostics to identify increasing agronomic stresses or pest infestations. Faced with a threat, farmers could use chemical sprays to selectively "switch on" specific resistance traits. These molecular biology and genetics advances enabled the agricultural sector to increase yields in the face of a range of stresses.

Increasing incomes in China, India and South East Asia had led to a large increase in demand for animal protein, particularly fish, meat and dairy products. This was exacerbated by the global decline of most wild fish stocks, which meant animal protein needed to replace part of the demand for protein that had formerly been met with oceanic fish. The loss of cheap sources of wild fish, particularly the collapse of the Alaskan pollock fishery in 2014, had also temporarily reduced aquaculture production for carnivorous fish species – such as salmon, tuna, cod, trout and prawns – that required fish protein. Several companies had invested in biotechnology research to produce fish proteins in GM algae, but it was not until 2019 that algal fish protein was available in sufficient quantity and at a low enough price to again support widespread aquaculture for carnivorous fish species.

The decline of fish stocks, although predicted as far back as the 1950s, was due to a continual failure to reach an enforceable international agreement to control overfishing. Careful genetic "fingerprinting" and tracking of remnant wild populations of tuna, cod, whiting, herring, salmon, sardines, pollock, haddock and other species were used to try to recover several fisheries.

Fictional Scenarios to 2030

The concerns in the Malthusian years over the security of supply for food, feed, and biomass for biofuels and industrial feedstocks had diminished, partly due to new agricultural biotechnologies for high-yielding food crops and dedicated energy crops such as GM grasses and eucalyptus varieties. The other reason was a substantial increase in agricultural land in South America and Africa. The international community had failed in its efforts to set rigorous life cycle standards for the carbon production and source of origin of both agricultural products and biofuels; consequently, high demand for grain for livestock and feedstocks for biofuels escalated the conversion of vast swathes of tropical savannah and rainforest to agricultural and biofuel crops. Unfortunately this released enormous reservoirs of carbon, damaging efforts to control global warming.

Global prosperity depended on strengthened trading rules under the WTO. Neither of the two major Asian powers, China and India, was able to produce enough food and feed to supply its own domestic needs. Both were major importers of food, feed, and biofuels from South America, Africa and North America, and exporters of high-value-added manufactured products. To reduce political tensions, the Food and Agriculture Organization (FAO) was given a mandate to maintain high global food reserves. It was widely believed that a repeat of the disaster of the Malthusian years could result in war without adequate global food reserves and free trade in agricultural commodities.

High energy-density biofuels were produced either from cane species or from cellulosic fermentation of low-lignin GM varieties of fast-growing grasses and trees. Biofuel production in temperate areas was mostly produced from GM grasses grown on marginal lands in Russia, Mongolia and the northern plains of the United States and Canada. Biofuel was also produced from trees in a few temperate countries, such as New Zealand, with ample low-cost, renewable forest plantations. Otherwise, the economics of production strongly favoured sub-tropical and tropical regions with ample rainfall, where biofuel production was ten times higher per hectare from tropical eucalyptus plantations than from trees in temperate zones such as Europe.

Sophisticated biorefineries, concentrated in the warm high-rainfall areas of South America, Africa, South East Asia and the Southern United States, produced little waste and could flexibly switch outputs in response to market prices. In addition to biofuel, many refineries could produce high-value oleochemicals and biolubricants for the chemical and manufacturing sectors and bioplastics sought by the automotive and manufacturing industries. Several high-value complex chemicals were produced by micro-organisms, developed using synthetic biology.

Four US-Brazilian agro-industrial conglomerates were responsible for 70% of global production of biofuels and biochemicals. To ensure supply and reduce costs, these firms maintained extensive GM cane and tree plantations to feed their biorefineries. Biofuels supplied 6% of global energy demand and were almost entirely used for transport. The major low-carbon energy sources for electricity generation were from nuclear, solar, geothermal, tidal and wind power.

The Middle East was a centre of research for the production of hydrogen fuel, algal fuels and synthetic biology. The cost of algal biofuels had been falling rapidly, due to a technical breakthrough that prevented bacterial infestation of unicellular algal biofuel farms.

Fictional Scenarios to 2030

Several energy consulting firms estimated that hydrogen and algal fuels could be cheaper than biofuels produced from cane or wood by 2032. In response, the four US-Brazilian conglomerates were investing heavily in biotechnology research to improve the competitiveness of high energy-density fuels from cane sugar and cellulosic crops.

Biofuel production was insufficient to meet all transportation needs. Consequently, transportation varied according to the opportunities within each region. Electrified public transport systems predominated in cities. Lightweight private vehicles built of composite biopolymers could run on an electrical charge for short distances or on a range of biofuels for longer distances. Due to high carbon taxes, petroleum use in 2030 was limited to feedstock material for bulk chemicals, air transport, and the production of electricity in combination with carbon capture systems.

Energy conservation and a gradual redesign of the structure of cities to accommodate higher densities encouraged more exercise from public transit use, bicycling and walking. A small reduction in food consumption due to higher relative food costs and increased exercise as part of daily life reversed the obesity epidemic that was a major health concern in 2010. Public opposition in developed countries to higher health premiums for risky personal behaviours had also declined over time. Both private and public health insurance premiums included reductions for indicators of healthy lifestyles, such as weight, blood pressure and diet. These were verified by annual check-ups with family doctors.

By 2030, comprehensive medical records systems had been gradually introduced in most health jurisdictions. These records were analysed to identify optimal treatment therapies and genetic risk factors for many chronic diseases. MeDFA provided a functioning incentive system that had helped to improve research efficiency by encouraging collaboration. The lack of patents after market entry meant that all products funded by MeDFA were produced as generics, reducing the cost of medical technology. Consequently, the populations of many developing countries could afford recent innovations in pharmaceuticals, diagnostics and medical devices.

It was no longer possible to speak of separate health biotechnology and pharmaceutical sectors. Biotechnological knowledge was used in all new drug development and in the development of many medical devices. However, the focus of healthcare research had partly shifted from pharmaceuticals to regenerative medicine, diagnostics and surgical techniques. Several debilitating chronic diseases such as cardiovascular problems, diabetes and arthritis were treated with tissue regeneration based on stem cells. The discovery of biomarkers for some early-stage cancers and bionanotech imaging technologies to detect them before metastasis (the major cause of cancer mortality) had opened up new opportunities for treatment through microsurgery and drug delivery systems based on nanotechnology.

Biomarkers for early-stage cancers improved survival substantially, but they were expensive because screening had to occur on a population scale. This substantially increased diagnostic costs, as 100 individuals would need to be screened each year after age 40 to detect one early-stage cancer. Part of the cost of screening and regenerative medicine was balanced by a fall in costs for chronic care. Small savings were also made from genetic screening of embryos for inherited diseases and serious risk factors. This led to a precipitous drop in the number of

Fictional Scenarios to 2030

babies born with such diseases (Campbell, 2008), many of which had required costly long-term medical treatment. However, costs started to creep up as the public began to use genetic screening to detect minor "flaws" or risk factors for chronic disease. There were heated public debates over the types of genetic factors that would justify aborting an embryo.

The main drivers for a continuation of high healthcare costs were the increase in neurodegenerative disease due to ageing population structures in Europe, China and Japan, and the research and application costs for predictive and preventive medicine. Neurodegenerative disease was viewed as the new cancer – greatly feared and with no effective cure in sight, despite billions of dollars spent on public and private R&D to find treatments.

Predictive and preventive medicine had created some notable successes in addition to the identification of biomarkers for early-stage cancer. Doctors were able to identify a risk of developing rheumatoid arthritis and several other autoimmune diseases, and to delay onset by an estimated average of ten years. For other diseases, testing for genetic risk factors and biomarker diagnostics could predict the onset of disease several years before the appearance of symptoms, but there were no effective therapies to prevent the disease from developing.

A five-year national experiment between 2024 and 2028 with predictive and preventive medicine in Denmark identified serious problems with the concept. With the exception of screening for cancer and rheumatoid arthritis after age 50, the experiment was judged to have caused almost as much misery as good. Knowing that one was at risk for serious chronic disease later in life created anxiety and depression among a large percentage of the population. Due to the probabilistic nature of risk factors, more people received screening or preventive treatment than benefited, driving up costs.

Danish parents quickly refused to let their children be tested for anything but serious treatable diseases that would appear within two years. Research showed that people were seeking quality of life and peace of mind. The overly enthusiastic application of predictive medicine appeared to have seriously reduced both. Older people particularly feared a loss of independence, so learning about a high probability of developing a debilitating neurodegenerative disease frequently caused serious depression and a lack of motivation.

The Danish experiment sparked intensive discussion internationally. Ethicists asked if the limits of medical intervention in healthcare had now been reached, since most people did not want to know if they faced serious health problems in the future. Scientists noted that with time, successful preventive therapies would be found for many of the diseases for which prevention was nonexistent or only partly successful. Public health researchers responded that part of the effectiveness of preventive medicine to date for cardiovascular disease and several cancers had been due to changes to diet, exercise, sleep, and an active social life – factors that had been known about for decades. Furthermore, a doctor could easily detect these types of major risk factors without the use of advanced medical technology.

The results of the Danish experiment led to new regulations for predictive and preventive medicine in many countries. Doctors were only permitted to test for diseases that could be cured or significantly delayed. Tests for diseases that could not be treated, or where early diagnosis made no difference to outcomes, were prohibited in most countries, except for research.

Fictional Scenarios to 2030

Predictive and preventive medicine had been expected in 2010 to automate healthcare. The role of the family doctor would be changed, from one who practices the "art" of medicine to a technician who identified individually optimised and evidence-based therapies, using software that analysed genetic and other diagnostic test results, medical histories, and behavioural and environmental data. By 2030, all of these systems were in place. The ability of doctors to ignore mandatory treatment protocols had declined, due to greater enforcement in managed healthcare systems and a change in medical school curricula. Doctors had not been turned entirely into technicians, however, as they played a key role in encouraging and supporting lifestyle changes.

Many people were living longer healthier lives due to improvements in healthcare and lifestyles. The retirement age in most OECD countries had been increased in step with increasing longevity: it averaged 69 years in 2030, preventing the expected pension crisis. As had been expected in 2010, information technology products and disease management systems increasingly permitted the elderly to live at home longer. This provided some healthcare savings, given the high cost of long-term in-patient healthcare. Some aspects of home care, such as automated health surveillance systems, were poorly accepted at first because patients saw it as an intrusion on their sense of independence (Dinesen *et al.*, 2008). With time, and remarketing as virtual "Health Buddies", they were widely accepted.

Pollution of fresh water supplies and oceans remained a serious problem. Coastal China, Eastern India, and the Gulf of Mexico were among the most polluted bodies of water on earth. Both India and China were investing in bioremediation techniques, improved agricultural systems and water conservation technologies to increase fresh water supplies and clean up polluted oceans. GM marine plants were used to revitalise marine areas that had become "dead zones" through industrial pollution and agricultural runoff. The marine plants were mechanically collected as a source of biomass for chemical biorefineries.

Scenario 2 – Uneven Development

2009 to 2014: Mixed progress

Regulatory systems posed significant constraints and costs on innovation systems, particularly in health and primary production. The cost of meeting regulatory requirements reduced the ability of small health or agricultural firms to invest in innovation. Small firms needed to both own valuable patents and receive financial support from either venture capital or large firms. One problem was increasing corporate concentration, which reduced the number of large firms – particularly in agricultural applications that were interested in buying new technology. This was a significant barrier when new technology threatened an existing technology owned by one of the major firms.

One effect was slow technical progress in agricultural biotechnology to develop cellulosic fermentation processes that jeopardised existing investments in starch based biofuels. The production of bioethanol from maize in the United States had doubled between 2007 and 2012, while European production of biofuels accounted for 15% of EU crop production by 2013.

Fictional Scenarios to 2030

Agricultural biotechnology for food and feed crops, controlled by five major global firms, was nevertheless a success. Food and feed production increased in South America, India and China due to new GM varieties of maize, wheat, rice and soybeans. However, European countries continued to place obstacles in the way of growing GM crops. That led to a major conflict with European livestock producers, who were paying increasingly higher prices for animal feed. This was partly caused by the high share of European crop production diverted to mandated biofuels, and partly due to a number of crop imports rejected at the border because of trace amounts of non-approved GM crops. The biofuel policy was highly controversial, with environmental NGOs arguing that European biofuel policy was contributing to rather than reducing global GHG production. A major cause was the destruction of tropical rainforests to create farmland for biofuel and other crops.

Agro-industrial firms in both Europe and North America had responded to biofuel mandates by investing in expensive infrastructure for crop-based biofuel production. They successfully lobbied governments to maintain mandates that favoured these biofuels. Slow progress in cellulosic fermentation research, combined with the low price support for cellulosic fuels in the United States and Europe, meant that cellulosic biorefineries were likely to be unprofitable for the foreseeable future. As a result, "green" investors in cellulosic biofuels shifted their investment portfolios to other energy sources, particularly solar, geothermal, and petroleum exploration.

In early 2014, under pressure from NGOs, the European Parliament ended all mandates for biofuels, although another explanation was a lack of public support for GHG initiatives after five years of below-average temperatures. A few months later the European Parliament accepted a plan to construct a network of nuclear power plants to supply 80% of the European Union's electricity. The announcement caused a sudden drop in petroleum and natural gas prices, due to expectations of a large future drop in imports from Russia. Agricultural commodity prices, in contrast, only dipped slightly after the end of the European Union biofuel mandate because of increased global demand for food and feed. As a consequence, the use of agricultural starches as a feedstock in Europe for industrial chemicals and polymers was replaced with petroleum feedstock.

A major development in health biotechnology occurred in early 2015, when two of the world's largest pharmaceutical companies and a major ICT firm formed a joint venture, TripleC, with the largest private healthcare provider in the United States, Consolidated Community Carers (CCC), serving 100 million people.[7] The venture had been initiated by CCC, which saw a major business opportunity in the FDA's requirements for compulsory post-marketing follow-up and pharmacogenetic information in clinical trials. The healthcare provider offered the two pharmaceutical firms full access to its members for clinical trials and use of its extensive medical records system, developed by the ICT firm. The medical records tracked patients as long as they were a member of CCC and contained information on prescribing histories, health outcomes, environmental risk factors such as diet and exercise and, increasingly, genetic information and biomarkers. In return, CCC demanded a 25% reduction off the lowest price agreement in the United States for drugs produced by the two pharmaceutical firms. An additional benefit, which was the main interest of CCC, was to be able to provide the highest level of care in the United States, and consequently charge an

THE BIOECONOMY TO 2030: DESIGNING A POLICY AGENDA – ISBN-978-92-64-03853-0 © OECD 2009

insurance premium over its competitors. The ICT firm was interested because of the potential market for automated diagnostic and home healthcare products.

As part of the agreement, CCC retained control over the types of pharmaceuticals, regenerative therapies and diagnostics that the two pharmaceutical firms would test on its members. This was to prevent the pharmaceutical firms from increasing costs to CCC by testing drugs with minor benefits over existing therapies. In addition, CCC would only be able to charge an insurance premium if it could offer better health outcomes compared to its competitors. It therefore had a strong economic incentive to encourage its two pharmaceutical partners to conduct research into therapeutically innovative therapies.

2015 to 2022: Turbulence

Overall, the world economy had experienced moderate economic development after the end of the global financial crisis in 2010, with rapid growth in China and India. Demand for energy, mineral resources and agricultural commodities returned to growth rates that were above the long-term trend. No agreement had been reached internationally on GHGs. Public interest in climate change had declined because temperatures had increased very little since 2007. Global scientists had warned in 2008 that this was only a temporary anomaly caused by a long cycle in the earth's orbit, and that it would end by 2020. This would be followed by a rapid increase in temperatures if GHG production was not reduced. This warning was believed in some capitals and ignored in most. Production of biofuels continued in the United States because of subsidies that were justified by energy security, and bioethanol continued to be profitable in Brazil without subsidies. Elsewhere there interest in biofuels and other low carbon energy sources declined.

On 11 September 2016 terrorists attacked three American oil refineries in Louisiana, Mississippi, and Texas, temporarily paralysing oil production in the United States. A fourth attack the next day in London released a suspected toxin that affected thousands of people with severe intestinal pains. None of the attacks caused any deaths. The cause of the intestinal illness was discovered within a few weeks to have been a synthetic bacterium, probably produced in a lab in the Western United States. Both events sent shock waves through the United States and Europe – partly because they were unexpected, since there had been no major terrorist attacks for years.

Governments were far more concerned about the attack on London than the oil refinery bombings. The use of a synthetic pathogen raised horrifying possibilities of what might be achievable with synthetic biology, and concerns that the comparatively harmless bacteria used in London was a signal of much worse to come.

These events caused an immediate shift in government priorities towards domestic security. All developed countries immediately introduced severe security restrictions on research into both synthetic life forms and GM. The high costs of meeting the security regulations caused most small firms active in agricultural and industrial biotechnology to abandon GM research. Between 2017 and 2025, the United States poured funds into biosecurity research to detect trace pathogens in agricultural commodities, water, and imported goods. The high salaries and research opportunities in biosecurity caused bioscientists who were previously active in

THE BIOECONOMY TO 2030: DESIGNING A POLICY AGENDA – ISBN-978-92-64-03853-0 © OECD 2009

industrial and agricultural firms to move to biosecurity research. Although developing countries, including Brazil, India and China, also introduced increased biosecurity measures, these were less stringent. Biotechnological research in the three countries was also dominated by government laboratories, where it was easy to implement improved security measures.

Concern over the ability of terrorists or pathogens to cross borders reduced international trade, particularly in agricultural commodities. The possibility of a deep economic depression in Canada and Mexico, both heavily dependent on trade with the United States, caused the two countries to agree to a NAFTA energy security zone. The goal – zero petroleum imports by 2025 – was met by a mix of energy conservation measures, expanded production from the Athabasca tar sands in Canada, and biofuel production.

Renewable biomaterials such as biodegradable oils, plastics, and industrial inputs received minimal attention in most developed countries. Governments were too distracted by fundamental concerns over security, and industrial firms faced serious difficulties in hiring bioscientists and in conducting biomaterials research. Interest in sustainable environmental practices and products remained at very low levels.

Research into biosecurity had several commercially valuable benefits. The development of water conservation and purification technologies for the purposes of domestic water security and industry development had positive impacts on agricultural production in several countries where droughts were common, including Australia, the United States, and Spain. New biosecurity technologies based on nanotechnology, biosensing, and molecular and genetic diagnostics benefited pest control programmes in agriculture, particularly for animals, but also for crops. A major benefit was the development of sensors that could instantly identify hundreds of varieties of microbes. These were widely used by doctors and in hospitals to identify sub-types of bacteria that were resistant to specific antibiotics and to determine if common ailments were caused by viruses or bacteria. These sensors turned into a front-line defence against the growing problem of antibiotic-resistant bacteria.

In contrast to these benefits, genetic modification of crops crawled forward in the United States under stringent new security regulations and a lack of bioscientists. Most agricultural researchers in academia concentrated on biosecurity. Only a few large firms remained active in GM crop development, and they concentrated on pest resistance. The production of pharmaceuticals or industrial chemicals in GM plants was prohibited in the United States and in Europe because of concerns that the technology might be used illegally by terrorists to produce poisons.

Consumers in developed and security-conscious nations looked for "local food" labels showing the distance travelled by a food commodity on its package. "Food miles" were displayed the distance food travelled from the time of its production until it reached the consumer. Although originally developed to assess the environmental impact of food, it was now used to assess its security, assuming that every unit of distance travelled increased its chances of being tampered with.

Patents for industrial, agricultural and security biotechnologies became increasingly expensive to maintain as the United States and European countries used the security clauses of the TRIPS agreement to block patents that could reveal any information of value to terrorists.

Fictional Scenarios to 2030

China and India provided patent protection, but it was difficult to enforce. The loss of effective patent protection was another contributor to the failure of biotech solutions in agriculture and industry.

The health sector was largely protected from the problems affecting the agricultural and industrial sectors, due to more competitive salaries. Furthermore, the US government increased funding for health research in the identification and treatment of new infectious pathogens.

In 2020, the TripleC joint venture had been shut down by its participating partners. It was replaced with a merger between CCC and the ICT firm and a friendly takeover by these two partners of the two pharmaceutical firms. The decision to move to an integrated firm was partly driven by frictions between CCC and the ICT firm on the one side, and the two pharmaceutical firms on the other, over the development of expensive drugs that were not particularly innovative. There were also disagreements over the use of regenerative medicine, which had been an increasing success but which threatened some of the markets of the pharmaceutical partners. The merged company was led by the CEOs of CCC and the ICT firm. The new TripleC was able to assemble new technology, build new types of expertise, surmount regulatory barriers to innovation and develop its new competition model. It had become very profitable, although so far largely on the basis of adopting new medical devices and regenerative therapies.

After the announcement of the merger, demand for membership in TripleC soared, due to expectations of significantly better healthcare services compared to competitors. This permitted TripleC to raise insurance premiums further. Due to logistical costs the business model was based on an upper limit of 100 million members, so there was no incentive to expand. Furthermore, the model depended in part on cherry-picking the healthiest Americans to reduce medical costs. The US Congress had banned health providers from requesting genetic information from potential patients. TripleC, however, was able to effectively screen its membership for the most expensive chronic diseases through routine medical check-ups and membership agreements to maintain weight within reasonable levels and follow age-adjusted exercise programmes. The firm avoided legislation in several states that prohibited insurers from refusing coverage by moving its head offices to Arizona.

Once accepted, new members underwent genetic screening to identify potential risk factors for chronic disease. This information was used both to design compulsory individual lifestyle programmes and in therapeutic research programmes.

The model in the United States was successfully copied in India and China, countries with poorly developed public healthcare systems and a burgeoning number of private sector healthcare firms. China's main healthcare firm was created out of a merger between a healthcare provider and several firms active in regenerative medicine, while the Indian firm followed the American example and was based on a merger between a pharmaceutical firm, healthcare provider, and an ICT firm. These firms and their business models were called Networked Health Providers (NHPs). The NHPs were leaders in translational medicine**.** With a large membership base and their own hospitals, they offered academics excellent facilities and access to their information databases.

Fictional Scenarios to 2030

While the profit base of any individual pharmaceutical in the portfolio of a NHP company was not comparable to that of a blockbuster drug, the co-ordination of a range of drugs and therapies proved to be a viable business model. The structure was also more effective than public agencies such as NICE in the United Kingdom in controlling excessive drug costs.

The fact that the main route to market for healthcare products was increasingly mediated and brokered via the NHPs meant that small health biotechnology firms could succeed financially with a much wider range of innovation strategies than was the case in 2015. Drug development no longer dominated health biotechnology; there was an equal focus on diagnostics and regenerative medicine. The fruits of public and private investment in life sciences began to emerge in new and often unexpected ways, stimulated by new types of partnership bringing together companies and individuals with biochemical, chemical, IT, physics and engineering expertise. NHPs sold therapies to each other, to public health systems, and to other private healthcare firms.

The NHPs benefited from an FDA requirement for pharmacogenetics to be used in clinical trials. The technology helped to identify ineffective drugs at an early stage of clinical trials, saving money. However, pharmacogenetics also led to a significant increase in the number of new innovative drugs on the market, stimulating a new round of basic research into new drug targets.

2022 to 2030: Partial recovery

In 2022 biotechnology was widely used in health and in biosecurity, but its application to industry and primary production was limited in developed countries. This was due to the high cost of meeting biosecurity rules, a lack of technological breakthroughs despite early promises and expectations, and a shortage of scientific researchers interested in either of these two applications. The European Union still banned GM crops. Science students were more interested in new challenges in nuclear, geothermal and solar research.

There were some successes. Brazil had developed economically competitive biorefineries for both biobutanol and bioplastics by 2025. Brazil benefited from the expertise of European enzyme companies that had moved most of their research operations to Brazil, China and India after the European and American restrictions on research into synthetic biology and GM organisms in late 2016. Researchers in India and South Africa had developed photosynthetic protein arrays on metallic frameworks that could efficiently produce solar electricity.

Industrial bioprocessing was centred in Brazil and India. Bioplastics were the biggest success of industrial bioprocessing and replaced most of the petroleum-based plastics globally, especially in Asia. Production was cheap and based on GM plant and microbial processes. Production used closed loop systems that recycled waste into feedstock. Microbes were also used to recycle bioplastics and bioplastic-containing products. Any form of waste was regarded by Brazilian and Indian researchers as a challenge to develop a microbial solution to waste recycling. Metabolic pathway engineering had a large part in developing this aspect of industrial biotechnology. The method, combined with synthetic biology, was used to develop microbes that could extract valuable metals, including uranium, from seawater.

Fictional Scenarios to 2030

Sustainable economic development in 2022 was patchy. Some regions, such as Europe and China, had invested substantially in nuclear power, ostensibly to reduce GHGs but also for energy security. GHG production in the NAFTA countries had increased due to extensive exploitation of tar sands, but conservation, as part of an energy security strategy, had mitigated the worst effects. Brazil, South Africa and India were the most carbon-neutral major economies, due to biofuels in Brazil and solar energy in South Africa and India.

Concern over GHGs and climate change grew into a serious global issue again by 2027, due to seven consecutive years of accelerated global warming. The increase in high temperatures and drought renewed interest in using GM technology to develop stress-resistant crop varieties. There was persistent lobbying of governments to simplify biosecurity legislation. China and India were first movers in this area, since they were increasingly concerned about the effect of increasingly erratic grain harvests in South America and Africa, their major source of grain imports.

The large increase in intensive dairy production in both China and India had allowed brucellosis, and in particular TB, to become major diseases of concern. Intensive hog production in South East Asia also resulted in an influenza outbreak in 2023. All of these emerging pandemics, including African Swine Flu in Kenya, were rapidly identified and contained, using real-time diagnostics and rapid response recombinant vaccine production methods developed as part of biosecurity research. Recombinant vaccines for livestock diseases were widely used. Some of these vaccines were produced in large quantities by the governments of China, Thailand and Vietnam, and used to inoculate livestock herds and human populations in South East Asia.

Biotechnologies for defence and health security applications (such as nanotech and biosensing) received further investment to support food security and traceability applications. For example, nanotech and biosensing technologies merged to provide biosensors capable of identifying nanoparticles of a pathogen or contaminant in crop or livestock shipments. Other technologies included skin tag scanners that identified livestock varieties within seconds, and microchips and accompanying scanners that provided a detailed history of individual animals and food products.

Up until 2028, biotechnology R&D was more extensively used for livestock than for crops, with marker-assisted selection and cloning used to develop disease-resistant varieties of livestock. An important area of research was the genetic sequencing of commercially valuable plant and animal species and of agricultural pests. The main motivation was to permit the rapid development of treatments for future crop and livestock diseases.

Global databanks of plant and animal DNA were maintained by the FAO and the National Institutes of Health (NIH) in the United States as part of biosecurity. The knowledge was applied in the 2020s to prevent illegal trade in biological materials. Illegal logging of natural forests had been virtually stopped by FAO monitoring systems, using biosensors that could identify illegal wood varieties and other plant products.

Some developing countries, particularly in parts of Africa, continued to struggle with periodic outbreaks of serious disease in farm animal populations. The continual pressure for increased productivity to feed a burgeoning population, together with pressure on land and

THE BIOECONOMY TO 2030: DESIGNING A POLICY AGENDA – ISBN-978-92-64-03853-0 © OECD 2009

water resources, resulted in stressed animals and poor management. These factors made disease outbreaks more likely. However, the eradication of rinderpest and the availability of better disease control through improved diagnostics and vaccines meant that eastern and southern Africa could compete with South America for meat production. As with South America, most of the animal products were exported to Asia.

European countries with public health systems were slow to adopt an integrated health system due to concerns over potential conflicts from a closer working relationship between for-profit firms and public health services. Consequently, European pharmaceutical firms struggled with funding, although they were able to benefit from pharmacogenetics and RNA interference in drug discovery. In addition, all drug firms in developed countries suffered from restrictions on the use of GM technology and synthetic biology to produce drugs. This had blocked low-cost production of complex biological and chemical molecules, increasing costs. In some cases, drugs could only be produced economically in India, where these technologies were still permitted.

The major success of the health NHPs had created new problems and threats to their business model by 2030. NHPs benefited from being able to charge high premiums for superior health services. This had helped to create a highly visible two-tier health system in the United States, China, India, and even the United Kingdom, where the National Health Service had evolved into a public-private NHP hybrid. A large fraction of society that could not afford to join NHPs was covered by "second class" traditional healthcare providers. These organisations had to purchase many new therapies from NHPs at high prices. In response to an ongoing political debate over NHPs, several developing countries with publicly funded healthcare systems were threatening in 2030 to invoke the opt-out clauses of TRIPs to produce patented therapies at low cost, instead of purchasing them from NHPs.

Notes:

1. As an example, bevacizumab extended median survival for colorectal cancer by 1.8 months, from 10.7 months to 12.5 months (NCI, 2005).

2. This trend was already visible in 2007. See Grésillon, 2008.

3. Intragenics uses GM technology to transfer gene constructs between plants that can interbreed under natural conditions.

4. 2005 USD, unadjusted for purchasing power parity.

5. 2005 USD, unadjusted for purchasing power parity.

6. Many of the characteristics of the treaty are derived from Love and Hubbard, 2007.

7. This example, and its continued development below, is inspired by the health scenario elaborated by Tait *et al.*, 2008.

Fictional Scenarios to 2030

References

Bezold, C. and J. Peck (2005), "Drug Regulation 2056", *Food and Drug Law Journal,* Vol. 2, pp. 127-136.

Bruinsma, J. (2003), *World Agriculture: Towards 2015/2030*, FAO, Rome.

Campbell, C. (2008), "Genetic Screening Raises Tough Ethical Issues", *The Star Ledger*, 10 March.

Dellenbach, R. (2008), "VC Funding for Biotech Companies Withering", *Genetic Engineering and Biotechnology News.*

Dinesen, B., *et al.* (2008), "Under Surveillance, Yet Looked After: Telehomecare As Viewed By Patients and Their Spouse/Partners", *European Journal of Cardiovascular Nursing*, Vol. 7, pp. 239-246.

EC (European Commission) (2007), *En Route to the Knowledge-Based Bio-Economy*, European Commission, Brussels.

EU KLEMS (European Union Capital (K) Labour (L) Energy (E) Materials (M) Service Inputs (S) Database) (2008), "Growth and Productivity Accounts", database, *www.euklems.net/eukdata.shtml*.

Grésillon, G. (2008), "La mondialisation 2.0 a commencé", *Les Echos*, 20 May.

German Ministry of Education and Research (2004), *Scenarios for a Bio-based Economy*, IFOK, August.

Gulliford, M. (2008), "Self Monitoring of Blood Glucose in Type 2 Diabetes", *British Medical Journal*, Vol. 336, pp. 1139-1140.

Houben, A., *et al.* (2008), "Engineered Plant Minichromosomes: A Bottom Up Success?", *The Plant Cell,* Vol. 20, pp. 8-10.

IBM (2006), *Healthcare 2015: Win-Win or Lose-Lose?*, IBM Global Business Services, Somers, New York.

Kay-Tee, K., *et al.* (2008), "Combined Impact of Health Behaviours and Mortality in Men and Women: The EPIC-Norfolk Prospective Population Study", *PLOS Medicine,* Vol. 5, pp. 39-47.

Love, J. and T. Hubbard (2007), "The Big Idea: Prizes To Stimulate R&D For New Medicines", *Chicago-Kent Law Review,* Vol. 82, pp. 1519-1554.

MacRae (2007), *Industrial Biotechnology to 2030, www.oecd.org/dataoecd/12/9/40922929.pdf*, accessed 11 December 2008.

Murphy, Angela M., *et al.* (2008), *Agricultural Biotechnologies to 2030*, *www.oecd.org/dataoecd/12/57/40920458.pdf,* accessed 11 December 2008.

NCI (National Cancer Institute) (2005), "Fact Sheet: Bevacizumab (Avastin) for Treatment of Solid Tumours: Questions and Answers", *www.cancer.gov/cancertopics/factsheet/AvastinFactSheet/.*

Neild, I. I. and Pearson (2005), *BT Technology Timeline*, British Telecom, London, August.

NZ MoRST (New Zealand Ministry of Research, Science and Technology) (2005), *Biotechnologies to 2025, www.morst.govt.nz/business/biotech-to-2025/.*

OECD (Organisation for Economic Co-operation and Development) (2006), *Biotechnology Statistics*, OECD, Paris.

OECD (2008), Structural Analysis Database (STAN), OECD, Paris.

Pharma Futures (2007), *Prescription for Long-term Value*, SustainAbility Ltd, London.

Perry, G. (2006), "The European Generic Pharmaceutical Market in Review: 2006 and Beyond", *Journal of Generic Medicines,* Vol. 4, pp. 4-14.

Smith, R. (2006), "Responding to Global Infectious Disease Outbreaks: Lessons from SARS on the Role of Risk Perception, Communication and Management", *Social Science and Medicine,* Vol. 63, pp. 3113-3123.

Smith, R. and M.M. Álvarez (2008), *Global Change and Health: Mapping the Challenges of Global Non-healthcare Influences On Health*, World Health Organization, Geneva.

Tait, Joyce *et al.* (2008), *Health Biotechnology to 2030*, OECD, Paris, *www.oecd.org/dataoecd/12/10/40922867.pdf.*

Tong, S. and C. Soskolne (2007), "Global Environmental Change and Population Health: Progress and Challenges", *EcoHealth,* Vol. 4, pp. 352-362.

USDA (United States Department of Agriculture) (2005), *Preparing for the Future*, USDA Advisory Committee on Biotechnology and 21st Century Agriculture, USDA, Washington, DC.

WBCSD (World Business Council for Sustainable Development Scenario Unit) (2000), *Biotechnology Scenarios 2000-2050: Using the Future to Explore the Present*, World Business Council, Geneva.

Zoellick. R. (2008), Speech to the Peterson Institute for International Economics, Washington, DC, 6 October.

Abbreviations and Acronyms

ADR	adverse drug reaction
AG	agronomic trait
AIDS	acquired immunodeficiency syndrome
ALL	acute lymphoblastic leukaemia
APHIS	Animal and Plant Health Inspection Service
BP	British Petroleum
BRIC	Brazil, Russia, India and China
BSE	bovine spongiform encephalopathy
CDER	Center for Drug Evaluation and Research
CGAP	Cancer Genome Anatomy Project
CGIAR	Consultative Group on International Agricultural Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DBF	dedicated biotechnology firm
DDT	dichlorodiphenyltrichloroethane
DHA	Department of Health and Aging (Australia)
DHHS	Department of Health and Human Services (United States)
DNA	deoxyribonucleic acid
DNDi	Drugs for Neglected Diseases Initiative
DOE	Department of Energy (United States)
EEC	European Economic Community
ELISA	enzyme-linked immunosorbent assay
EMEA	European Medicines Agency
EU KLEMS	European Union Capital (K) Labour (L) Energy (E) Materials (M) Service Inputs (S) Database
FAO	Food and Agriculture Organization of the United Nations
FDA	Food and Drug Administration (United States)
FFN	functional foods and nutraceuticals
GAO	Government Accountability Office (United States)
GBOARD	government budget outlays and appropriations for research and development

GDP	gross domestic product
GHG	greenhouse gas
GM	genetically modified *or* genetic modification
GVA	gross value added
HAS	*Haute Autorité de Santé*
HIV	human immunodeficiency virus
HR	human resources
HT	herbicide tolerance
HT-IR	combined herbicide tolerance and insect resistance
IAVI	International AIDS Vaccine Initiative
IB	industrial biotechnology
ICH	International Conference on Harmonisation
ICT	information and communication technology
IEA	International Energy Agency
IMSR	improvement of medical service rendered
IPCC	Intergovernmental Panel on Climate Change
IPO	initial public offering
ISAAA	International Service for the Acquisition of Agri-biotech Applications
ISO	International Organization for Standardization
IT	information technology
IVD	*in vitro* diagnostic
IVF	*in vitro* fertilisation
LCA	life cycle analysis
M&A	mergers and acquisitions
mAb	monoclonal antibody
MAS	market-assisted selection
MEOR	microbial enhanced oil recovery
MSR	medical service rendered
Mtoe	million tons of oil equivalent
NAFTA	North American Free Trade Agreement
NCE	new chemical entity
NGO	non-governmental organisation
NICE	National Institute for Clinical Excellence
NIH	National Institutes of Health (United States)
NMA	*Noordwijk* Medicines Agenda
NME	new molecular entity
OECD	Organisation for Economic Co-operation and Development
OIE	World Organisation for Animal Health
PCR	polymerase chain reaction
PCT	Patent Cooperation Treaty
PDO	polydioxanone

PGD	preimplementation genetic diagnosis
PHA	polyhydroxyalkanoates
PHB	polyhydroxybutyrate
PPP	purchasing power parity
PQ	product quality
PVC	polyvinyl chloride
QALY	quality adjusted life years
R&D	research and development
RFA	Renewable Fuels Association
RNA	ribonucleic acid
RNAi	RNA interference
SARS	severe acute respiratory syndrome
SM	small molecule
SME	small- and medium-sized enterprise
SNP	single nucleotide polymorphisms
Synbio	synthetic biology
TB	tuberculosis
TRIPS	Trade-Related Aspects of Intellectual Property Rights (WTO)
UN	United Nations
UNU-MERIT	United Nations University Maastricht Economic and Social Research and Training Centre on Innovation and Technology
USDA	United States Department of Agriculture
USITC	United States International Trade Commission
USPTO	United States Patent and Trademark Office
VC	venture capital
WHO	World Health Organization
WTO	World Trade Organization

Table of Contents

List of tables

List of figures

List of boxes