Chapter 29
The Role of Biotechnology in Energy and Environment

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29.1 Introduction

At present, the global economy depends to a large extent on energy, chemicals and materials derived from fossil carbon sources, mainly petroleum. The present level of global energy consumption, production and industrial growth is not sustainable because it is only made possible by continued withdrawals from the stored 'bank' of fossil carbon, which is finite and not renewable (Organisation for Economic Cooperation and Development (OECD) 2001). Current methods for hydrogen production are inefficient, and some have a worse carbon footprint than burning petroleum-derived fuels (http://www.transportation.anl.gov/pdfs/TA/165.pdf). Because of this, it is essential that we find more sustainable means of generating liquid transportation fuels. The replacement of fossil fuels with more carbon-neutral and renewable sources has become a key necessity of the time. The realization of the adverse effects of greenhouse gas emissions on the environment, together with declining petroleum reserves, has speeded up the quest for sustainable and environmentally benign sources of energy. There is now widespread acknowledgement that renewable bio-resources have considerable potential to increase national energy security and to minimize anthropogenic effects on the environment (Young). If we wish to achieve both energy security and global-warming objectives through a standard, then it would be appropriate to partition the standard with a higher fraction being cellulose-based fuels (Eaglesham and Hardy 2007).

Current International Energy Agency (IEA) projections see a rapid increase in biofuel demand, in particular, for second-generation biofuels. A key question is how large a role could biomass play in responding to the nation's energy demands? The aim of the study is to identify opportunities and constraints to potential production of second-generation biofuels. Its potential role in the future energy supply, the likelihood and potential impact of deploying genetically modified (GM) perennial

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energy crops and the role of biotechnology to meet the dual challenges of biomass recalcitrance and large-scale sustainable production are issues of interest.

29.2 Path to a Sustainable Future—The Bio-Based Economy

Over the long term, we must displace petroleum—old biomass—with new biomass, with practices that preserve wildlife habitats, soil quality, water quality, maintain or increase farm income, encourage rural development and reduce greenhouse gas emissions. Renewable energy from our land is the most socially acceptable, environmentally friendly and economically feasible of all the choices. The proposition that energy can be obtained from biomass with a decisively positive energy balance (Farrell 2006; Lovins 2004) and at a scale sufficiently large to have a substantial impact on sustainability and security objectives is both supported by several recent studies and much more widely accepted now than only a few years ago (Lovins 2004; Greene et al. 2004; Lynd 2007; Perlack et al. 2005). Future increases in biomass production per unit land and fuel production per unit biomass could together result in a roughly tenfold increase in land fuel yield compared with today enabling scenarios in which biofuels play a large energy service supply role (Lynd 2007). There is also increasing recognition of the potential for environmental benefits—including greenhouse gas mitigation, improved soil fertility and water quality and improved wildlife habitat—if cellulosic crops were to be incorporated into the agricultural landscape (Greene et al. 2004; Jordan et al. 2007). So, developing a sustainable economy more extensively based on renewable carbon and eco-efficient bioprocesses (a 'bio-based economy') is one of the key strategic challenges for the twenty-first century (OECD 2001).

29.3 First-Generation Biofuels

Biofuel production has increased dramatically since 2000 impacting markets for food and fuel. During recent years, the production of many first-generation biofuels has faced heavy criticisms. The potential social, economic, environmental and human rights impacts of biofuels have been much debated and have been the subject of considerable controversy, for example, the UN special rapporteur on the Right to Food highlighting grave concerns that 'the sudden, ill-conceived, rush to convert food—such as maize, wheat, sugar and palm oil—into fuels is a recipe for disaster' (John et al. 2010; UN 2007). Biofuels do not provide the substantial benefits they were first perceived to offer, and there is also a growing understanding that their production imposes significant costs on environmental preservation and food security (Sexton 2009). In addition to the food/fuel dilemma, sugar and starch crops require substantial inputs of fertilizers and pesticides, and life-cycle analyses indicate that the production

Table 29.1 Biofuel production in top 10 countries (2011). (Source: Renewable 2012 Global Status Report)

Country	Fuel ethanol	Biodiesel	Total
	(Billion litres)		
United States	54.2	3.2	57.4
Brazil	21.0	2.7	23.7
Germany	0.8	3.2	3.9
Argentina	0.2	2.8	3.0
France	1.1	1.6	2.7
China	2.1	0.2	2.3
Canada	1.8	0.2	2.0
Indonesia	0.0	1.4	1.4
Spain	0.5	0.7	1.2
Thailand	0.5	0.6	1.1
World total	*86.1*	*21.4*	*107.0*

of bio-ethanol from corn has a net CO_2 emission rather than being carbon-neutral (Hill et al. 2006; Runge and Senauer 2007). The economic incentive to import biofuels, especially biodiesel from tropical countries, threatens the rain forests that provide enormous climate-moderating and habitat resources for all citizens in the world (Eaglesham and Hardy 2007). Current biofuels create a trade-off between food and fuel. The World Bank has identified much larger impacts from biofuels on food markets; biofuels are responsible for three-fourths of a 140 % increase in food prices from 2002 to 2008, or roughly a 50 % increase in the past year (Mitchell 2008) (Table 29.1).

29.4 Second-Generation Biofuel: A Sustainable Energy Solution

As the world entered its first food crisis in more than 30 years, focus is shifting to next-generation technologies that reduce the competition between food and fuel for staple crops and land (Sexton 2009). Second-generation feedstock and technologies promise to bring large improvements, as many fast-growing trees and grasses are perennials and require little cultivation once established, while sequestering much more carbon. Further, cellulosic alternatives can be grown on marginal land, require little fertilizer or water and have higher energy content. It is widely recognized that production of cellulosic crops could have substantially more positive environmental attributes than production of corn, soy or other annual row crops (Farrell et al. 2006; Hammerschlag 2006; Greene et al. 2004). Moreover, whereas oil and coal are unevenly distributed among countries, all countries could generate some bioenergy from domestically grown biomass of one type or another, thereby helping to reduce their dependence on imported fossil fuels (Hazell and Pachauri 2006). In fact, cellulose is the most abundant biological material on earth. India has nearly 500 million t of biomass waste available annually, and only 170 million t is used (Munshi 2011).

29.5 Projections of Future Demand for Biofuels

Second-generation biofuels are not yet produced commercially, but a considerable number of pilot and demonstration plants have been set up in recent years. Demand for second-generation biofuels is growing, driven by ambitious biofuel mandates, in particular, in OECD countries, and a growing desire by scientists and policy makers to ensure the sustainability of biofuel production. IEA projections see biofuels, in particular, second generation ones, as one of the key technologies to decarbonize the future transport sector. Projections see a rapid increase in biofuel demand, in particular, for second-generation biofuels, in an energy sector that aims on stabilizing atmospheric CO_2 concentration at 450 parts per million (ppm) (IEA 2009a).

The World Energy Outlook 450 Scenario for 2030 projects biofuels to provide 9% (11.7 EJ) of the total transport fuel demand (126 EJ) by 2030 (IEA 2009a). Another IEA work extends the analysis to 2050. The *Blue Map Scenario3* of *Energy Technology Perspectives 2008* (IEA 2008b) targets 50% reduction in global CO_2 emissions by 2050. In this scenario, biofuels provide 26% (29 EJ) of total transportation fuel (112 EJ) in 2050, with second-generation biofuels accounting for roughly 90% of all biofuel. More than half of the second-generation biofuel production is projected to occur in major economies and developing countries with China and India accounting for 19% of the total production. Another 35% would take place in other developing countries, underlining the importance of further research on framework conditions for second-generation biofuel production outside the OECD region (Table 29.2).

Table 29.2 Projections of future demand for biofuels

	World Energy Outlook 2009		Energy Technology Perspectives 2008	
	Reference Scenario for 2030	*450 Scenario* for 2030	*Baseline Scenario* for 2050	*Blue Map Scenario* for 2050
World primary energy demand	16,790 Mtoe (705.2 EJ)	14,389 Mtoe (604.3 EJ)	23,268 Mtoe (977 EJ)	18,025 Mtoe (750 EJ
Biofuels	167 bn lge (5.6 EJ)	349 bn lge (11.7 EJ)	133 bn lge (4.5 EJ)	870 bn lge (29.1 EJ)
Share of total transport fuel	4.0%	9.3%	2.2%	26.0%

Source: IEA 2008a (This scenario models future energy demand in light of a global long-term CO_2 concentration in the atmosphere of 450 parts per million, which would require global emissions to peak by 2020 and reach 26 Gt CO_2-equivalent in 2030, 10% less than 2007 levels. The total global primary energy demand would then reach 14, 389 Mtoe (604 EJ) in 2030); IEA 2009a (This scenario models future energy demand until 2050, under the same target as the World Energy Outlook (WEO) 450-Scenario (i.e. a long-term concentration of 450 ppm CO_2 in the atmosphere). Global primary energy demand in this scenario reaches 18,025 Mtoe (750 EJ) in 2050)

29.5.1 Biomass Yield

Based on the expectation that agricultural and forestry residues could be the most sustainable feedstock for second-generation biofuels, an availability assessment is undertaken to explore what role this feedstock could play in global transport fuel supply. Using crop and round wood production data from the Food and Agricultural Organisation (FAO), the production of residues and technically feasible second-generation biofuel yields are assessed for 2007 and 2030. Amounts of biofuels are calculated under two assumptions: one that 25 % of all residues are available, as indicated in previous studies, and the other that only 10 % of residues could be used sustainably (Stat FAO 2009; FAO 2003).

Considerable amounts of second-generation biofuels could be produced from available agricultural and forestry residues, e.g., even if only 10 % of the global agricultural and forestry residues were available in 2030, roughly 50 % of the forecasted biofuel demand in the World Energy Outlook 2009, 450 Scenario, could be covered—equal to approximately 5 % of the projected total transport fuel demand by that time. A fourth of the global residues could contribute 385–554 billion lge (13.0–23.3 EJ) globally. These amounts of second-generation biofuels are equal to a share of 10.3–14.8 % of the projected transport fuel demand in 2030, and could fully cover the entire biofuel demand projected in the WEO 2009, 450 Scenario. This represents significant potential considering that no additional land would be required to produce these amounts.

29.5.2 Biomass Feedstock: Central Challenges

It is critically important to develop a clear understanding of the central challenges that must be addressed to achieve more widespread bioenergy use. The cost of processing corn to sugar adds a modest amount to the feedstock carbohydrate cost. In contrast, the current cost of converting cellulosic biomass to sugar roughly doubles the carbohydrate purchase cost, eliminating the cost advantage of cellulosic biomass relative to corn. The substantial potential benefits of large-scale energy production from cellulosic feedstock will be difficult to realize until sugars can be produced from the feedstock at a cost competitive with production from corn and other more readily processed raw materials. The sole barrier to the widespread adoption of cellulosic alternatives is technological. The enzymes needed to convert cellulose are prohibitively expensive and inefficient. Table 29.3 compares the value of various potential energy sources in commonly reported units and in $/gigajoule (GJ). Cellulosic biomass at $50/metric t is less expensive than all sources listed except coal, and it is advantageously priced relative to coal if the anticipated cost of carbon sequestration is included. At $50/t ($3/GJ), the purchase price of cellulosic biomass on an energy basis is the same as oil at $17/barrel (Lynd et al. 2008).

Table 29.3 Prices of selected energy sources. (Lynd et al. 2008)

Energy source	Price	
	Common ($/amount)	$/GJ[a]
Petroleum	50/bbl	8.7
Gasoline[b]	1.67/gallon	13.7
Natural gas[c]	7.50/scf	7.9
Coal[d]	20/t	0.9
Coal with carbon capture[e,f]	106/ton	4.8
Electricity	0.04/kWh	11.1
Soy oil[g]	0.23/lb	13.8
Corn kernels[h]	2.30/bu	6.6
Cellulosic crops[i]	50/t	3.0

bbl barrel; *scf* standard cubic foot

[a] Assumed lower heating values: petroleum, 5.8 GJ/bbl; gasoline, 5.1 GJ/bbl; natural gas, 37.3 MJ/m3; coal, 23.3 MJ/kg; soy oil, 36.8 MJ/kg; corn kernels, 16.3 MJ/kg; cellulosic crops, 17.4 MJ/kg (Schubert 2006)

[b] Wholesale price, average 2004–2006 (http://www.eia.doe.gov/)

[c] 2005 annual average US wellhead price (http://www.eia.doe.gov/)

[d] 2004 annual average US open market price (http://www.eia.doe.gov/)

[e] Cost of carbon capture assumed to be $150/ton carbon (http://www.fossil.energy.gov/programs/sequestration/capture/)

[f] Coal carbon content assumed to be 57% (dry weight basis) (White and Whittingham 1983)

[g] Average price 2004–2005 (http://www.usda.gov/)

[h] Average price 2002–2005 (http://www.ers.usda.gov/Data/FeedGrains)

[i] Price representative of typical values assumed for energy crops in the literature (for example, McLaughlin et al. 2012)

29.6 Biofuel Production Costs

29.6.1 Central Issue: High Cost of Processing

At present, the production of such fuels is not cost-effective because there are a number of technical barriers that need to be overcome before their potential can be realized. Cost estimates for second-generation biofuels show significant differences depending on plant complexity and biomass conversion efficiency. Important factors include annual full-load hours of plant operation, feedstock costs and capital requirements. Accordingly, biofuel plants with a higher biomass-to-biofuel production ratio are typically able to accept higher biomass supply costs compared with less efficient plants (IEA 2010).

A projection shows short- and long-term production costs of different biofuels under two oil price scenarios (IEA 2010). With oil at USD 60/bbl, production costs for both Biomass-to-Liquid (BTL)-diesel and lignocellulosic ethanol are currently in the range of USD 0.84–0.91/lge, and thus are not competitive with fossil fuels and most first-generation biofuels. In the long term, however, with increasing plant capacities and improved conversion efficiencies, both BTL diesel and lignocellulosic ethanol could be produced at significantly reduced costs. In this case, production costs are projected to be approximately USD 0.62/lge for lignocellulosic ethanol and USD 0.58/lge for BTL-diesel (IEA 2009c). The estimated production costs are less than those for rapeseed biodiesel, but still more expensive than gasoline and other first-generation biofuels.

With oil at USD 120/bbl, production costs rise to USD 1.07/lge for BTL-diesel and USD 1.09/lge for lignocellulosic ethanol. In the long term, prices are projected to fall to USD 0.73/lge for BTL-diesel and USD 0.72/lge for lignocellulosic ethanol. Therefore, with reduced overall costs and oil price at USD 120/bbl, second-generation biofuels could be produced at lower costs than gasoline and rapeseed biodiesel and close to the costs of corn ethanol (IEA 2009c).

Currently, the largest cost factor for BTL-diesel production is the capital costs. They account for 49 % of total production costs with oil at USD 60/bbl and 51 % of costs with oil at USD 120/bbl. Feedstock costs account for 35 and 33 % in the two scenarios, whereas all other factors like Operations & Maintenance (O&M) costs, energy demand and others have a share between 1 and 4 %. For lignocellulosic ethanol, feedstock costs are currently the largest cost factor, accounting for 42 % of total production costs in both oil price scenarios. Capital costs are approximately 38 % with oil at USD 60/bbl and approximately 42 % with oil at USD 120/bbl (IEA 2010).

The immediate factor impeding the emergence of an industry converting cellulosic biomass into liquid fuels on a large scale is the high cost of processing. Experts disagree about when facilities to convert lignocellulose to fuel will operate on an industrial scale—it may be 5 years or 10 or 20 years but all agree that bringing down costs will be the key (Charlotte 2006). An important point to be noted is that when oil refining was maturing as a technology, it was not nearly as cheap as it is now. Converting lignocelluloses to ethanol is estimated to account for 70 % of the cost, and raw materials 30 %, the exact opposite of oil refining today. We have a lot of room to move to make our systems cost competitive (Dale 2005). Within the processing domain, potential Research and Development (R&D)-driven improvements in converting biomass to sugars offer much larger cost savings in comparison with improvements in converting sugars to fuels. The central issue to be addressed is thus improving technologies to overcome the recalcitrance of cellulosic biomass. The cost of converting biomass to sugars must be lowered to have a cost advantage relative to sugar production from more easily hydrolyzed raw materials, such as corn. The cost of sugar production from cellulosic biomass can be lowered by improved enzymes, improved processes for biomass pre-treatment, new biomass feedstock that are more easily processed or a combination of these. The second central challenge is sustainable production of cellulosic biomass in very large amounts using a feasible amount of land (IEA 2010).

The large biomass demand (up to 600,000 t/year) for a commercial second-generation biofuel plant requires complex logistics systems and good infrastructure to provide biomass at economically competitive costs. This is a particular challenge in the rural areas of the countries where poor infrastructure, complex land property structure and the predominance of small land holdings increase the complexity of feedstock logistics (IEA 2010).

29.6.2 A Renewed Commitment to Biotechnology

Given the potential for biotechnology to not only produce more productive food and energy crops but also develop more efficient biofuel conversion processes, it seems there is cause for optimism that the global challenges of the new century can be met. The contribution of biofuels to solving the present energy crisis relies on a technological breakthrough to meet the projected demand. The latest developments in the areas of enzyme production and cell wall biology bring the goal of sustainable biofuel production closer to realization. Once efficient enzymes are available in large quantities, potential ethanol feedstock expands beyond starch-based crops like corn and sugar to the entire class of cellulosic plants, including grasses, trees and shrubs. To ensure a successful deployment of second-generation biofuels, technologies require intensive R&D efforts over the next few decades. Investments in research and development by both governments and private companies provide scope for a fast learning curve in the whole area (http://genomicsgtl.energy.gov/centers/, http://www.ebiweb.org/). In many developing countries, the framework conditions needed to set up a second-generation biofuel industry are not currently sufficient. The main obstacles that need to be overcome include poor infrastructure, lack of skilled labour and limited financing possibilities. Capacities should then be built slowly but continuously to avoid bottlenecks when new technologies become technically available and economically feasible. To ensure technology access and transfer, cooperation on R&D between industrialized and developing countries as well as among developing countries should be enhanced.

Biotechnological approaches are likely the most powerful approach available to address the dual challenges of biomass recalcitrance and large-scale sustainable production (Hawken et al. 1999). Biotechnology can be powerful drivers of productivity growth, but it demands increased investment and reduced regulation. We need to promote greater sustainability and responsibility in the way we use the resources of the planet, but it is equally clear from past experience regarding GM crops that it is imperative to inform the rest of the society in as clear a way as possible about the potential benefits of this move as well as the perils of not taking action.

29.7 Discussion

The potential to use available residues from the agricultural and forestry sector to produce second-generation biofuels underscores the need for technology development. In the short term, this is likely to take place in developed countries and some large emerging economies like those of Brazil, China and India, where sufficient financing and R&D capacities can be provided.

The way to avoid the negative effects of producing biofuels from food supplies is to make lignocellulosic-derived fuels available within the shortest possible time. This process involves an unprecedented challenge, as the technology to produce these replacement fuels is still being developed. However, the immediate use of first-generation biofuels involves putting in place logistic changes to use biofuels (engine modification, distribution, production plants, etc.). This commitment to biofuels in the present will make the transition to the second generation of biofuels more economically convenient.

The production of biofuels from cellulosic biomass requires a new industry to be born—many factors have to be put in place ranging from the technical to the political (Eaglesham and Hardy 2007). Thus, there is potential and realizing even a fraction of the anticipated benefits of biomass energy will require manpower, investment, innovation and technology deployment on a vastly larger scale. If developing economies are to participate beneficially in the growth of renewable bioenergy production, and to also maintain adequate levels of food security, a complementary set of aggressive investments are necessary. Such investments could bring about benefits for consumers of both food and energy, while also contributing to the broader growth of their economies and improved livelihoods. A comprehensive approach is needed for rapid development of alternative fuels involving plant breeders, agronomists, bioprocess engineers, biotechnologists and microbiologists.

Technical development will mainly take place in OECD countries and emerging economies with sufficient Research Development and Demonstration (RD&D) capacities like Brazil, China and India. To ensure a successful deployment of second-generation biofuels technologies requires intensive RD&D efforts over the next 10–15 years. In many developing countries, the framework conditions needed to set up such an industry are not currently sufficient. The main obstacles that need to be overcome include poor infrastructure, lack of skilled labour and limited financing possibilities.

29.8 Conclusions

Really, if our aim is to find ways and means to minimize dependence on fossil fuels on a lasting basis then biofuels of second generation is one strong option to ensure diversification in energy supply and sustainability. Demand for second-generation biofuels is growing due to mandates in developed countries and a growing support by scientists and policy makers. Demand for second-generation biofuels will increase substantially by 2030 and even more by 2050 to the extent of biofuels meeting 26% of fuels needed in the transport sector of which the major share is expected to be second-generation biofuels. It is clear that liquid biofuels hold the potential to provide a more sustainable source of energy for the transportation sector, if produced sensibly. A mere 10% of the global biomass availability in 2030 can meet roughly 50% of the forecasted demand for biofuels. This represents a significant potential considering that no additional land would be required to produce these quantities.

The assessment undertaken shows that considerable amounts of second-generation biofuels could be produced from available agricultural and forestry residues. Assuming even a conservative value of 10% availability of global agricultural and forestry residues for second-generation biofuel production, there should be enough feedstock remaining for traditional uses. BTL-diesel, for instance, could cover approximately 45% of the projected biofuel demand or 4% of the total transport fuel needs in 2030 in an energy scenario where considerable emission reductions are a priority (WEO 2009 *450 Scenario*). This represents significant potential considering that no additional land would be required to produce these amounts.

Under the 25% scenario, these residues in 2030 could yield 385 billion lge of lignocellulosic ethanol, 391 billion lge of BTL-diesel or 554 billion lge of bio-Synthetic Natural Gas (SNG). This equals a share of 10.1–14.6% of the total transport fuel demand in 2030. This indicates that the volume is more than the entire biofuel demand.

The IEA WEO (2012) 'Current Policies' scenario projects that advanced biofuels like biomass-to-liquid biodiesel or cellulosic ethanol, will become commercial by 2025, while the '450' scenario projects this happening much sooner, by 2015 (REN21 2013). Cellulosic ethanol plants are still considerably more expensive to build than corn ethanol plants in the United States, by a factor of 2–3 in higher investment costs. So, costs will have to decline significantly, although cellulosic feedstock is cheaper, so capital investment costs give only part of the picture. Experts point to continuing incremental improvements in costs through a variety of possible processes, including hybrid processes combining biochemical and thermo-chemical conversion (REN21 2013).

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