Production of Bio-ethylene

Technology Brief

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organization dedicated to renewable energy. In accordance with its Statute, IRENA's objective is to "promote the widespread and increased adoption, and the sustainable use of all forms of renewable energy". This concerns all forms of energy produced from renewable sources in a sustainable manner and includes bioenergy, geothermal energy, hydropower, ocean, solar and wind energy.

As of December 2012, the membership of IRENA comprises some 160 States and the European Union (EU), out of which 104 States and the EU have ratified the Statute.

About IEA-ETSAP

The Energy Technology Systems Analysis Programme (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA), first established in 1976. It functions as a consortium of member country teams and invited teams that actively cooperate to establish, maintain, and expand a consistent multi-country energy/economy/environment/engineering (4E) analytical capability.

Its backbone consists of individual national teams in nearly 70 countries, and a common, comparable and combinable methodology, mainly based on the MARKAL / TIMES family of models, permitting the compilation of long term energy scenarios and in-depth national, multi-country, and global energy and environmental analyses.

ETSAP promotes and supports the application of technical economic tools at the global, regional, national and local levels. It aims at preparing sustainable strategies for economic development, energy security, climate change mitigation and environment.

ETSAP holds open workshops twice a year, to discuss methodologies, disseminate results, and provide opportunities for new users to get acquainted with advanced energy-technologies, systems and modeling developments.

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Insights for Policy Makers

Ethylene is one of the basic organic chemicals serving as feedstock for a number of downstream chemical products. With a production exceeding 140 million tonnes per year, ethylene is by far the largest bulk chemical (in volume) used for the production of around half of all plastics. The demand for ethylene is expected to continue to rise, particularly in the emerging economies. Today, almost all ethylene is produced from petroleum derivatives, but biomass can also be used as an alternative feedstock for the production of bio-ethylene. Ethylene and bio-ethylene are chemically identical, so existing equipment and production capacity can use both to produce plastics or other downstream products. At present, the first bio-ethylene plants in Brazil and India account for approximately 0.3% of the global ethylene capacity, and the largest plants produce around 200 kt of bio-ethylene per year. However, the global market for biopolymer production is growing fast and several production plants are under construction or planned (e.g. China).

Bio-ethylene is produced from bio-ethanol, a liquid biofuel that is widely used in the transportation sector with an annual production of around 100 billion liters. At present, the United States (using corn) and Brazil (using sugarcane) are the largest producers of bio-ethanol, accounting for respectively 63% and 24% of the global production. Ligno-cellulosic biomass from wood and straw can also be used to produce bio-ethanol, but related production processes still need a full commercial demonstration. The advantage of using ligno-cellulosic feedstock instead of sugar and starchy biomass (e.g. sugarcane and corn) is that it does not compete with food production and requires less or no arable land and water to be produced.

The potential for bio-ethylene production is large, but its implementation will depend on the future availability and price of the biomass feedstock, which are linked to developments in food demand and the use of biomass for biofuels, heat and electricity production. The cost of bio-ethylene is highly dependent on the local price of the biomass feedstock and is still higher than that of petrochemical ethylene in most situations. At the same time, bio-based plastics can attract premium prices on the market, which could make them a competitive business in regions with abundant and cheap biomass feedstock. In Brazil and India, due to the availability of cheap biomass resources and Brazil's long-standing tradition of using bio-ethanol for transportation purposes, bio-ethylene costs are estimated to be almost equal to petrochemical ethylene.

The environmental performance of bio-ethylene depends largely on the regional conditions for the production of bio-ethanol, the greenhouse gas (GHG) emissions eventually due to land use changes, and the conditions of the incumbent energy systems. In general, bio-ethylene can significantly reduce the environmental impact of the chemical industry. Based on recent estimates, bio-ethylene can reduce GHG emissions byup to 40% and save fossil energy by up to 60% compared to petrochemical ethylene. In addition, bio-ethylene and other bio-based products made from local resources can reduce a country's dependence on fossil energy imports and stimulate local economies.

Biomass availability and the price gap with petrochemical ethylene are the two most important determinants for the future of bio-ethylene, although bio-ethylene can also contribute to energy security in oil-importing countries. While promoting the optimal use of biomass, including cascading use in various sectors of the economy, policy measures can support the deployment of bio-ethylene production capacity by supporting the use of bio-based materials via incentives, carbon tax schemes, eco-labeling or information campaigns, and removing import tariffs on bio-ethanol. In any case, future fossil fuel prices will remain a key factor in determining to what extent bio-ethylene can substitute for petrochemical ethylene.

Highlights

- **Process and Technology Status –** Ethylene, which is produced from petrochemical feedstock, is one of the most important platform chemicals in use today. Bio-ethylene made from bio-ethanol (from biomass) represents a chemically identical alternative to ethylene. Compared to the petrochemical equivalent, the main advantages of bio-ethylene are that it can reduce greenhouse gas (GHG) lifetime emissions (from both production and use) and the dependence of the chemical industry on fossil fuels. Bio-ethanol can be obtained by fermentation of sucrose feedstock (e.g. sugarcane) and from starchy biomass (e.g. corn) by hydrolysis followed by fermentation. These two production routes are well-developed and used to produce bio-ethanol for the transport sector in countries and regions (e.g. Brazil, the U.S., Europe and China). Besides sugarcane and corn, ligno-cellulosic biomass can also be used as a feedstock, but the conversion into bio-ethanol is more challenging and costly due to the biomass chemical structure. If technology advances overcome these issues, bio-ethanol and bio-ethylene production from ligno-cellulosic biomass could become economically attractive. In Brazil, bio-ethylene production is already economically competitive due to the ample availability of cheap sugarcane feedstock, extensive experience in ethanol production and increasing oil prices. This has led to new sugarcane-based bio-ethylene capacity. A new plant producing 200 kt per year is already in operation.

- **Performance and Costs –** Bio-ethylene production based on sugarcane is estimated to save about 60% of fossil energy compared to petrochemical production as the process can also produce electricity. Associated greenhouse gas (GHG) emissions from cradle-to-factory gate are about 40% less than the petrochemical production. In comparison, bio-ethylene from corn and ligno-cellulose save less energy and GHG emissions because related processes do not export electricity. However, ligno-cellulosic bio-ethylene would be much less demanding in terms of land use. The production costs of sugarcane bio-ethylene are very low in Brazil and India (i.e. around USD 1,200/t bio-ethylene). Chinese production based on sweet sorghum is estimated at about USD 1,700/t. Higher costs are reported in the United States (from corn) and in the European Union (from sugar beets) at about USD 2,000/t and USD 2,600/t, respectively. At present, the cost of ligno-cellulose-based production is estimated at USD 1,900-2,000/t in the U.S. In comparison, the cost of petrochemical ethylene is substantially lower (i.e. USD 600-1,300/t), depending on the region with a global average of USD 1,100/t. The current production cost of bio-ethylene is between 1.1-2.3 times higher than the global average petrochemical ethylene, but ligno-cellulosic bio-ethylene is expected to reduce the gap in the near future.

- **Potential and Barriers –** If all bio-ethanol currently produced for the transport sector (i.e. 61 million tonnes) were to be converted into bio-ethylene, this bio-ethylene would meet about 25% of current global demand. Projections suggest that bio-ethylene could meet between 40-125% of the global demand by 2035, depending on scenarios and taking into account co-products. However, several industrial sectors (e.g. transportation fuels, power generation and the chemical industry) might compete for the availability of biomass feedstock, and starchy and sucrose biomass alone cannot meet the total demand without competing with the food production industry. As a consequence, the development of cheap and sustainable conversion processes of ligno-cellulosic biomass is crucial to increasing the basic resources of sustainable biomass. Oil prices will also have a key impact on bio-ethylene market uptake. As far as GHG emissions are concerned, to better reflect the environmental advantages of biomaterials, policy measures should account for life cycle emissions of products, not only the chemical sector on-site emissions occurring during the production process.

Process and Technology Status

Ethylene is a platform petrochemical for direct or indirect production of most important synthetic polymers, including high- and low-density polyethylene (HDPE and LDPE), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET) (Shen et al., 2010).

Until the 1940s, ethylene was produced via ethanol dehydration, but with the advent of the economically attractive steam cracking process (Morschbacker, 2009; Kochar et al., 1981), almost all ethylene production is now based on various petroleum-based feedstock, including naphtha (mostly in Europe and Asia), ethane and, to a lesser extent, propane and butane in the Middle East and North America. The total production capacity reached 138 million tonnes (Mt) per year in 2011 (OGJ, 2011). However, increasing fossil fuel prices and concerns over greenhouse gas (GHG) emissions have now focused the attention on renewable feedstock for bio-ethylene production. As a consequence, bio-ethanol obtained from various biomass has been considered as an attractive precursor of bio-ethylene due to its technical and economic potential.

Bio-ethanol can be produced by the fermentation of a variety of plant biomass, which is then converted to bio-ethylene via catalytic dehydration[1]. Compared to the petrochemical route, this process can save GHG emissions in the product's entire lifecycle [2] because the plant feedstock absorbs CO2 from the atmosphere during its growth. In Brazil, the availability of low-cost sugarcane and bio-ethanol production, along with environmental advantages has recently led to investments in facilities for production of bio-ethylene and its downstream products (e.g. bio-PE).

Bio-ethylene is chemically identical to petroleum-based ethylene. Therefore, no new technology is required for conversion into downstream products. This technology helps reduce Brazil's oil dependence and stimulates the local economy and employment. However, extensive production of bio-ethylene can compete with food and feed production for the availability of arable land. In addition, if pristine land is converted into arable land for biomass production, this causes increased CO2 emissions, which can offset the environmental benefit (Bos et al., 2010).

- **Production Process and Feedstock –** The first step in bio-ethylene production is the creation of bio-ethanol from biomass feedstock. This is a well-known process as bio-ethanol is now used as a transportation fuel. Three types of biomass can be used (Balat et al., 2008): sucrose, starchy and ligno-cellulosic feedstock.

  Sucrose biomass (e.g. sugarcane, sugar beets and sweet sorghum) is relatively easy to break down as sucrose is a disaccharide, which can be directly fermented into bio-ethanol by yeast. Currently, two-thirds of sucrose biomass consists of sugarcane grown in (sub-)tropical regions, mostly in South America, with significant amounts in Asia, while one-third consists mostly of sugar beets grown in temperate regions, mainly in Europe. Sugarcane offers a high sugar yield plus ligno-cellulosic by-products (e.g. bagasse, leaves), which can be used for heat and power (Morschbacker, 2009). At present, Brazil is a leading country for the production of sugarcane bio-ethanol.

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[1] See IEA-ETSAP and IRENA Technology Brief P10 "Production of Liquid Biofuels" (September 2012) for more information on bio-ethanol.

[2] Life cycle refers to all steps involved in a product's manufacture, use and waste management (e.g. raw materials extraction, processing, production, transportation, use, repair, disposal). For a complete understanding of a product's environmental impact, all stages of the life cycle need to be assessed.

Starchy biomass (e.g. wheat, corn and barley) contains cellulose polysaccharides (i.e. long chains of D-glucose monomers), which must first be converted into a glucose syrup by either enzymatic or acidic hydrolysis. Glucose is then fermented and distilled into bio-ethanol. Currently, most starch-based bio-ethanol is produced in the United States from corn.

Ligno-cellulosic biomass (e.g. wood, straw, grasses) consists mostly of three natural polymers: cellulose, hemicelluloses and lignin. Ligno-cellulosic biomass forms the largest potential source of bio-ethanol because it is widespread and largely available at low cost. It can also be grown as a perennial crop on low- quality land with attractive yields, costs and low environmental impact (Balat et al., 2008). However, the conversion of ligno-cellulosic feedstock into bio-ethanol is more difficult and costly. Lignin forms highly branched structures that are bound to cellulose and are hard to break down by microbial systems. This makes the hydrolysis process and the final bio-ethanol relatively expensive though costs have come down significantly over the last decades, and large commercial production is about to start (e.g. POET, 2011).

In addition to hydrolysis and fermentation (i.e. the biochemical route), ligno-cellulosic biomass can be converted into ethanol by thermo-chemical processes (Foust et al., 2009). These involve feedstock gasification (i.e. production of syngas) and subsequent conversion into ethanol by fermentation or catalytic conversion (Foust et al., 2009). A number of new commercial-scale bio-ethanol production facilities based on the thermochemical route have been announced (Coskata, 2011; Enerkem, 2011), but they are not yet linked to the production of bio-ethylene.

Once bio-ethanol has been produced and purified to chemical grade, it is converted to bio-ethylene by an alumina or silica-alumina catalyst. One tonne of bio-ethylene requires 1.74 tonnes of (hydrated) bio-ethanol (Kochar et al., 1981). Conversion yields of 99% with 97% selectivity to ethylene have been achieved (Chematur, n.d.). The reaction is endothermic and requires a minimum theoretical energy use of 1.6 gigajoules (GJ) per tonne of bio-ethylene. While the ethanol-to-ethylene (ETE) process is relatively simple, it has scarcely been used in the last decades. Table 1 provides an overview of the capacity of current and planned facilities where bio-ethylene or its downstream products are produced with ETE technology. The current production capacity is about 375 kilotonnes (kt) per year, of which 200 kt/y are used for producing polymers (bio-PE) and the remainder for producing bio-based ethylene glycol (EG). Most of the capacity under construction also focuses on production of non-polymer ethylene derivatives, such as EG and ethylene oxide (EO), which could later be used for producing polymers.

Performance and Costs

- **Environmental Performance –** Table 2 provides environmental indicators for bio-ethylene production, based on lifecycle assessment (LCA) studies by Liptow and Tillman[3] (2009), Seabra et al. (2011) and the BREW project (Patel et al., 2006). The studies serve different purposes and use different approaches with regard to geographical and temporal scope, methods and system boundaries. Therefore, the information in Table 2 is not intended for comparison but to provide an up-to-date review of environmental indicators.

  According to the detailed LCA by Liptow and Tillman (2009), if compared to petrochemical production, sugarcane-based bio-ethylene can save about 19 GJ of non-renewable energy (60%) per tonne of output and emit about 0.7t of CO2eq (40% less). Seabra et al. (2011) estimate 12 GJ/t and higher CO2eq emissions 1.4 tCO2eq per tonne of bio-ethylene, excluding carbon sequestered in bio-ethylene. Patel et al., 2006 estimate 3.1 tCO2eq/t ethylene.

  Using the same approach to analyse 21 diverse bio- materials, the BREW project includes production from sugarcane, corn starch and ligno-cellulosic feedstock (Patel et al., 2006). Results show that bio-ethylene from corn starch and ligno-cellulose can save respectively 40% and 100% of non-renewable energy compared to petrochemical ethylene. Bio-ethylene from sugarcane can save up to 150% of energy, accounting for sugarcane co-products, such as electricity and heat from bagasse. The GHG emissions reductions are estimated at 120% from sugarcane[4], 45% from corn starch and 90% when using ligno-cellulosic biomass (all taking sequestered carbon into account). Land use is higher for sugar cane (0.48 ha/t) and corn (0.47 ha/t), whereas ligno-cellulosic biomass requires only 0.19 ha/t because all biomass material can be converted to ethylene.

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[3] The Liptow and Tillman (2009) and Seabra et al. (2011) reports study the production of bio-PE and bio-ethanol, respectively. Their results have been adapted to reflect the production of bio-ethylene (Table 2).

[4] Part of the reason why the GHG emission savings for sugarcane are so high is because this system exports electricity. The BREW study uses the average emissions from power generation in the EU-15 as a reference, meaning that renewable electricity can substantially reduce emissions. The other two studies take the Brazilian power sector as a reference, which has lower emissions per unit of electricity generated due to the large share of hydropower.

The GHG emissions from biomass products could be influenced by the additional emissions due to possible land use change (LUC) for biomass growth. New agricultural activity can lead to the removal of above- and below-ground biomass, soil organic carbon, litter and dead wood from pristine lands (Hoefnagels et al., 2010), which involve additional release of GHG emissions. These emissions are very significant but difficult to estimate. In spite of developments in LUC modeling (Wang et al., 2011), no standard methodology exists yet and calculation methods have a large impact on the results (Wicke et al., 2012). Liptow and Tillman (2009) show that the inclusion of the LUC emissions more than doubles their estimated CO2eq emissions but state that the uncertainty involved is very high. In conclusion, the original land use prior to biomass cultivation is a highly important determinant in estimating the emissions associated with biomass-based products.

- **Production Costs –** Table 3 presents an overview of bio-ethanol and bio-ethylene production costs in different regions, including a discussion and cost comparison with other studies. Production from starchy and sucrose feedstock is based on IRENA analysis, whereas production from ligno-cellulosic biomass is based on other literature.

  According to the IRENA analysis, the production cost estimates of bio-ethylene from starchy and sucrose feedstock show that Brazil and India are relatively cheap compared to other countries at around USD 1,200/t (see Table 3). Chinese production based on sweet sorghum is estimated at around USD 1,650/t. The production in the U.S. and the EU are estimated to be the most expensive at USD 2,000/t and USD 2,500/t, respectively. The biomass feedstock accounts for about 60% of the bio-ethanol production costs. In turn, the bio-ethanol cost accounts for about 60-75% of the bio-ethylene production cost, depending on the region (65% on average).

  Bio-ethanol production from ligno-cellulosic biomass via biochemical processes was estimated to cost about USD 750/t in 2012, assuming mature technical and economic conditions[5]. This leads to a bio-ethylene production cost of around USD 1,900/t and is slightly cheaper than the current thermochemical production routes at about USD 2,000/t. When compared to the U.S. target of reaching one USD/gallon bio-ethanol with ligno-cellulosic feedstock (i.e. USD 340/t bio-ethanol), the present bio- and thermo-chemical production routes are still more than twice as expensive.

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[5] These estimates are about 12% lower than the retail price estimates provided in the IEA-ETSAP and IRENA Technology Brief P10 on liquid biofuels.

Compared to bio-ethylene, petrochemical ethylene is cheaper: the global weighted average production cost is about USD 1,100/t, but in regions where cheap feedstock is available, the production cost could be as low as USD 600/t (IRENA analysis). Therefore, the present market position of bio-ethylene is very challenging, and it is expected that production will develop only in niche markets, such as Brazil.

To put the above discussion in the right perspective, it should be noted that publically available information on involved technologies is limited because of data confidentiality regarding technologies that are still in the start-up phase. Various inputs used in the IRENA analysis could differ significantly from the reference assumptions. For example, long-term contracts could offer lower prices for fuels, electricity and feedstock than those included in FAOstat[6]. In addition, local conditions can have a substantial impact on the production costs, particularly the feedstock prices, which account for about 65% of bio-ethylene production costs. Energy prices, discount rates and wages determined by local economic conditions also play a role. Uncertainty ranges are therefore estimated for model inputs, and production costs are given within an indicative range based on sensitivity (Table 3).

According to Table 3, Brazil is an exception compared to most regions because bio-ethylene production costs are lower than the petrochemical equivalent[7]. A number of possible reasons can explain this difference. For instance, bio-ethanol production from Brazilian sugarcane is well-developed as bio-ethanol has been widely used in Brazil as a transportation fuel since 1975 (Mitchell, 2011). Inexpensive sugarcane and large-scale bio-ethanol production and experience (e.g. demand was estimated at 22.5 billion liters in 2009/2010; Mitchell, 2011) have made Brazilian bio-ethanol relatively cheap compared to other regions. In contrast, ethylene production from steam cracking is relatively expensive in Brazil due to the high prices of imported petroleum products (e.g. naphtha, accounting for 60-70% of the production costs).

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[6] FAOstat product prices are assumed to include profits for the feedstock producers. By using them, the IRENA analysis represents a situation in which feedstock production and bio-ethanol production are not integrated. Back-integrating production could therefore yield lower production costs. Furthermore, it is assumed that bio-ethanol and bio-ethylene production are completely integrated.

[7] Although less information is available, India may have similar regional advantages since it is the second largest sugar cane producer worldwide and because a bio-EG production facility has been operational since 1989 (see Table 1).

Apart from Brazil, bio-ethylene production is typically more expensive than petrochemical ethylene, and producers may be hesitant to invest in this novel production route. To overcome these barriers, producers may set a premium price on their products. In 2007, Braskem determined a premium price for bio-PE of about 15-30% compared to petrochemical PE (Braskem, 2007). However, for widespread implementation of bio-ethylene in the long term, its prices need to be comparable to, and competitive with, petrochemical ethylene, particularly because there are no differences in chemical characteristics. Among bio-ethylene production routes, ligno-cellulosic bio-ethylene has the potential to become far cheaper than sugar- or starch-based production because 100% of the biomass material can be used. However, it could still take years for ligno-cellulosic production to reach this stage.

- **Capital Costs –** Based on the most recent investment information, the capital costs for bio-ethylene production range between USD 1,100-1,400 per tonne. The capital cost of Braskem's 200-kt/yr facility was estimated to be around USD 278 million (i.e. USD 1,390/t bio-ethylene; CT, n.d.;a). Mitsui and Dow have spent approximately USD 400 million for their joint venture to produce 350 kt/yr (i.e. USD 1,140/t bio-ethylene; Mitsui, 2011). It is unclear if more investment will be required later on in this project. Finally, Solvay Indupa has invested USD 135 million for a new PVC plant with a capacity of 60 kt/yr bio-ethylene; that is USD 2,250/t bio-ethylene, including related investments for the PVC plant (Conti, 2008).

Potential and Barriers

- **Potential –** The current market for bio-based polymers is small. Braskem's 200kt/yr bio-PE plant already accounts for 28% of total current biopolymer production capacity (European Bioplastics, 2011). By 2013, global biopolymer production is expected to grow to 2.4 Mt/yr, of which about 0.6 Mt/yr is bio-PE from bio-ethylene (Shen et al., 2009). Although growth is fast, the share of biopolymers will remain limited for some time at least as total production of plastics is over 250 Mt/yr (Shen et al., 2009).

  The implementation of bio-ethylene also depends on the amount of bio-ethanol available. The International Energy Agency (IEA) estimated that in 2009 about 1.6 EJ (or 61 Mt) of bio-ethanol was consumed for road transportation (IEA, 2010b). If all this bio-ethanol were to have been consumed for bio-ethylene, 35 Mt/yr of bio-ethylene would have been produced. This is equivalent to about 25% of the current global ethylene production capacity (all based on fossil-fuel feedstock; OGJ, 2011). The bio-ethanol production is expected to increase to 5-12 EJ/yr in 2035 (a factor of 3-7.5 compared to current levels), or 110-255 Mt/yr, depending on the development scenario applied (IEA, 2010b) [8]. If all of this were converted to bio-ethylene, it would meet between 41-125% of the projected ethylene production volume (i.e. between 205-266 Mt/yr in the Baseline scenario; IEA, 2009).

- **Barriers and Policy Needs –** Various barriers currently exist to the wide use of bio-ethylene. The current production of bio-ethylene from sugarcane in Brazil provides a good platform to build on. In Brazil (and in the United States), costs have already come down significantly (Van den Wall Bake, 2009 and Hettinga, 2009), and this trend is expected to continue with increased yields (e.g. due to genetic crop modification) and improved process management. However, the Brazilian production conditions are difficult to replicate in other areas. For example, production of sucrose or starchy feedstock large enough to supply bio-ethanol for large-scale bio-ethylene production is difficult to obtain in other areas. In addition, the conversion of food plantations to bio-ethanol production can increase food prices with a dramatic impact on developing countries (OECD, FAO, 2011). The only way to address this challenge is through biochemical or thermochemical conversion of ligno-cellulosic biomass into ethanol (Balat, 2011), which, if it can be made cheap and competitive, can enlarge the basic feedstock availability with minor or no impact on food production (Philippidis, 2008). Abundant biomass resource is the key to scale-up production and reduce bio-ethanol costs, and commercial projects based on ligno-cellulosic biomass are currently supported by policy incentives and government loans in many countries.

  From a technology perspective, there are two areas where solutions are required: improving the conversion process of ligno-cellulosic material (Mabee and Saddler, 2010) and reducing the costs of hydrolysis (Morschbacker, 2009; Patel et al., 2006). Current research efforts focus on modifying microbes for both hydrolysis and fermentation, thus decreasing the cost of hydrolysis enzymes or looking for new, undiscovered enzymes. Results are expected in the near future.

  Future prices of biomass feedstock are subject to significant uncertainty and linked to developments in food demand and biofuels for transportation. In this

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[8] Estimated using the expected volumetric growth of biofuels and assuming an ethanol share of 75% in global biofuels consumption in 2035, as in the IEA's New Policies scenario.

competitive situation, policy should determine the optimum distribution of biomass feedstock to various branches of the economy. Promotion policies for blending bio-ethanol with gasoline are already in place in the U.S. and parts of the EU (Pires, Schechtman, n.d.) and could limit the amount of biomass available for chemicals. While sustainable alternatives exist for transportation (e.g. electric vehicles), in any case the chemical sector will require a source of carbon, which can only be provided by sustainable biomass or petroleum.

Future oil prices will also play a key role in determining to what extent bio-ethylene can substitute for petrochemical ethylene. Depending on assumed policy routes, the IEA (IEA, 2010b) projects crude oil prices in 2035 between 2009 USD 90-135 per barrel. This difference could have a significant impact on the economic attractiveness of bio-ethanol and bio-ethylene production. Removing subsidies to fossil fuels, as recently recommended by the IEA and OECD (OECD, 2011), will help close the price gap between petrochemical and bio-based products.

Some kinds of ethanol import duties should also be removed. The European Union, for example, levies an import tariff on ethanol (Vermie et al., 2009) of up to USD 310/t. This import duty represents an important policy barrier to bio-ethylene production based on imported ethanol in the EU.

In general, the policy to promote the use of bio-ethylene needs to go beyond the current framework and look, not only at the direct emissions from production processes, but also at the life cycle of CO_2 emissions reductions. Credit should be granted to entire life cycle CO_2 benefits. This would also mean that carbon tax systems would more effectively motivate companies to produce bio-based products because they would offer larger CO_2 emission reductions. Policy measures could also include eco-labeling of bio-based chemicals and polymers, information campaigns and subsidies to producers (Hermann et al., 2011).

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Table 1 – Overview of Current and Planned Plants for Ethylene Production from Bio-ethanol[a]

Location	Company	Start-up year	Bio-ethylene capacity, kt/yr	Final product	Biomass feed-stock type	Source
Operational						
India	India Glycols Limited	1989	175[b]	Bio-EG	Molasses	IGL, 2011
Brazil	Braskem	2010	200	Bio-PE	Sugarcane	Braskem, 2007; CT, n.d.;[a]
Under construction						
Brazil	Solvay Indupa	2011	60	PVC	Sugarcane	Solvay, 2007
Taiwan	Greencol Taiwan Corporation	2011	100	Bio-EG	Sugarcane (from Brazil)	Petron, 2010; CT, n.d.;[b]
Brazil	Dow/Mitsui	2013	350 (expected)	Bio-PE	Sugarcane	Dow, 2011; Mitsui, 2011
Status unknown						
China	Sinopec	1980s	9	Bio-ethylene		Tan, 2008
China	BBCA group	2004	17	Bio-ethylene		Tan, 2008
China	Yongan Pharmaceuticals	2011	42[b]	Bio-EO		Rightler, 2011; SD, 2008
China	Jilin Bohai	2012	63[b]	Bio-EO		Rightler, 2011; SD, 2008
China	Heyang Bio Ethanol Co.	2013	80[b]	Bio-EO/EG		Rightler, 2011; Jiaozou, 2010
China	Sinopec Sichuan Vinylon Works		10	Bio-ethylene	Cassava	SVW, 2011

a) Data based on publically available information, not necessarily up-to-date. The list can miss small-scale pilot plants. b) Data refer to the capacities of bio-EO or bio-EG only. Actual bio-ethylene capacity is unknown.

Table 2 – Environmental Indicators of Cradle-to-Factory-Gate Bio-ethylene Production (Data given as per Tonne of Ethylene)

Study and Methodology	Feed-stock type	Net non-renewable energy use (GJ/t)	Renewable energy use (GJ/t)	GHG emissionsa (t CO2eq/t)	Land use (ha/t)
Liptow and Tillman (2009) – Consequential LCA of bio-PE production – Brazilian sugarcane conversion to bio-PE, transport to Sweden; and European crude oil to PE – System expansion, except for the crude oil route – Includes LUC GHG emissions – Excludes polymerisation and transportation Brazil to Sweden	Sugar-cane	12	53	1.0 (– 3.1)	n.a.
	Crude oil	31	0	1.7 (– 0)	n.a.
Seabra et al. (2011) – LCA of bio-ethanol production in 2008 – Brazilian sugarcane process to bio-ethanol – System expansion for electricity generation from bagasse – Excludes LUC GHG emissions – Includes conversion to bio-ethylene (Liptow and Tillman, 2009)	Sugar-cane	12	n.a.	1.4 (– 3.1)	n.a.

BREW Project – Patel et al. (2006) – Analysis of 21 bio-chemicals, three feedstock and 95 processes – Generic process with no specific location – Price-based approach accounting for co-products price; system expansion for co-products and exported energy; mass-based when no system expansion is possible – Includes present and future technology – Excludes LUC GHG emissions – GHG values exclude sequestered carbon	Corn	40	64	2.5 (– 3.1)	0.47
	Sugar-cane	-30	155	– 0.9 (– 3.1)	0.48
	Ligno-cellulose	1	108	0.5 (– 3.1)	0.19
	Naphtha cracking	66	0	1.3 (– 0)	n.a.

a) Values between brackets refer to the renewable carbon sequestered in ethylene (i.e. the CO2 stored in biomass during plant growth). This amounts to 3.1 t CO2eq/t for bio-ethylene (Patel et al., 2006) and is 0 for petrochemical production.

Table 3 – Overview of Estimated Production Cost for Bio-ethanol and Bio-ethylenea, (All Costs in 2009 USD/tonne

Loca-tion	Feedstock type	Ethanol production cost		Ethylene production cost		Source
		Mean	Range[a]	Mean	Range[a]	
IRENA estimates – Starch- and sucrose-containing feedstocks						
U.S.	Cornb	800	690 – 1,070	2,060	1,700 – 2,730	IRENA analysis
Brazil	Sugarcanec	420	360 – 560	1,190	970 – 1,630	IRENA analysis
India	Sugarcane	440	370 – 580	1,220	1,000 – 1,670	IRENA analysis
EU	Sugar beets	1,070	930 – 1,390	2,570	2,180 – 3,380	IRENA analysis
China	Sweet sorghum	630	520 – 800	1,650	1,340 – 2,180	IRENA analysis
Other sources – Ligno-cellulosic feedstocks						
U.S.	2012 state-of-the-art estimate (biochemical)	750		1,910[d]	1,820 – 2,080[b]	NREL, 2011
U.S.	Corn residue (thermochemical)	790		2,000[d]	1,900 – 2,170[b]	Poet, 2011
IRENA estimates – Reference production routes						
U.S.	Target of USD 1/gallon bio-ethanol	340		1,080	980 – 1,250	IRENA analysis
Global	Steam cracking (petrochemical ethylene)	n.a.		1,100[e]	600 – 1,300[e]	IRENA analysis

The IRENA bottom-up analysis refers to the 2009 situation; the bottom-up production cost methodology is based on Hermann and Patel, 2007 and feedstock prices on FAOstat; energy prices originate from various sources (e.g. IEA, 2010a; EIA, 2011). Discount rates are between 7.5-15%. Capital costs for bio-ethanol plants are taken from Tao and Aden (2009) and Maung and Gustafson (2011). Capital costs for bio-ethylene plants are taken from CT (n.d.). Other process data of bio-ethanol and bio-ethylene are from Seabra et al., 2011; Perrin et al., 2009; Li, 2010; Xunmin, 2009; Li and Chan-Halbrendt, 2009.

a) Range represents worst- and best-case scenarios (i.e. changing all inputs at the same time to the most optimistic or pessimistic values).

b) The production cost for bio-ethanol for corn does not include credits associated with selling the by-product, distiller's grain with solubles (DDGS), on the market. If included, the 0.3 kg of DDGS produced per litre of bio-ethanol would provide a co-product credit of USD 55/t Bio-EtOH, which is a 7% decrease of the production costs (using 2009 prices of DDGS from USDA of about USD 140/t DDGS).

c) The best estimate of USD 420/t for production costs is about 20% lower than the estimates for retail prices provided by Technology Brief P10. The estimate, however, does include the burning of the by-product bagasse to generate electricity, which is a common practice in Brazil.

d) Ethanol production costs are taken from original sources and the ethylene production costs are calculated by the IRENA model. Because original sources provide a single value for bio-ethanol production costs, the bio-ethylene costs show a smaller range compared to starchy and sucrose feedstock.

e) Calculations are for eight world regions varying from USD 600 (Middle East) to USD 1,300 (former USSR); average is USD 1,100/t. All are based on an oil price of USD 75/bbl. Estimates are based on publicly available energy prices, which are considered high compared to long-term contract prices for ethylene producers.

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