Chapter

# Alcohol Fuels: Current Status and Future Direction

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## Abstract

Worldwide demand for liquid fuels will increase steadily, but not in the form of $CO_2$-emitting scheme, rather in a renewable and sustainable way. Keywords for the future energy direction must be clean, renewable, and sustainable. Alcohol fuels are again becoming a frequent keyword for clean fuel utilization in connection with mitigation of climate change and clean fuel technology suitable for less-used local energy sources. There are a lot of interests in widening the raw feedstock to lignocellulosic biomass and algae from grain-based raw materials. Using the locally available, underutilized feedstock becomes important for local energy security as well as an option for distributed energy infrastructure.

**Keywords:** alcohol fuel, biomass, bio-ethanol, low-grade feedstock, alternative fuel

## 1. Introduction

High strategic risk of dependence on imported energy sources is attracting profoundly alarming concerns as indicated by recent international trend and past experience. Self-sufficient energy supply system is at least needed to maintain a certain minimum living standard in a nation in general and the society in particular so that easy access to domestic and neighboring energy sources is a key factor to maintain. Alcohol fuels are very promising alternative energy sources from this point of view.

Worldwide demand for liquid fuels will increase steadily at least through the mid-twenty-first century, but not in the form of $CO_2$-emitting scheme, rather in a renewable and sustainable way. Actually, there had been many options that can use locally plentiful energy resources, typically in a biomass type.

The major energy source nowadays is most certainly (hydrocarbon) gas, electricity, and liquid fuel, which is almost unanimously agreed upon. Current energy infrastructure has already been solidly established with (hydrocarbon-based) gas, electricity, and liquid fuel as convenient energy sources and such energy infrastructure appear to get more and more solidly implemented. Inconvenience related to the utilization of solid fuels is no longer tolerable, and rapid commercialization of electric vehicle is also foreseen in the near future. Liquid fuel gets replaced to the ultra-clean fuel that meets the ever-stringent environmental regulations. Electricity is produced from atomic energy, coal, natural gas, and petroleum oil products, but safety, environmental friendliness, and global warming issues must also be comprehensibly considered. Many Asian countries almost exclusively depend on imported liquid natural gas for energy source. This raises dual issues on the feasibilities of steady supply in energy sources and of reasonably affordable cost. In fact, natural gas that emits 40–55% level of reduced $CO_2$ evolution compared to coal is surely a promising source of energy. Ethanol produced from sugarcane is one of the most carbon-efficient biofuels available globally, with life cycle greenhouse gas emissions around 70% lower than conventional hydrocarbon transport fuels [1]. Current worldwide trend of shifting to alternative clean, sometimes ultra-clean, gas/liquid fuel from more conventional liquid fuel of gasoline/light oil necessitated a new definition of role and position of alcohol fuels in the emerging picture.

Alcohol fuels were originally regarded as an alternative energy sources for petroleum oil to realize energy independence during oil crisis of the 1970s. A brief look into the history of bio-ethanol shows Ford Motor Company's development of ethanol-fueled car in 1899, which was terminated by low-priced gasoline then. Oil crisis of the 1970s revived similar interest in the form of gasohol by mixing ethanol, which was developed and commercialized mainly in Brazil.

The first starting point on alcohol fuels in the 1970s tells the basic background at that time. It is prompted by concerns about reliance on foreign sources of oil and a desire to support domestic agriculture. In the United States, in particular, E10 gasohol was implemented during the oil crisis of 1970s to reduce petroleum oil dependence and simultaneously to utilize surplus farm crops. At present, E15 product with 15% ethanol content is distributed for consumer market.

In the twenty-first century, alcohol fuels are again becoming a frequent keyword for clean fuel utilization in connection with mitigation of climate change and clean fuel technology suitable for less-used local energy sources. As a matter of fact, demand for alcohol fuels is mainly derived from socioeconomic and political motivations rather than from consumer conscious reasons and economic viability.

The centralized energy system that emphasizes cost-effectiveness had diminished the key driving force for technological advances in alcohol fuels. Petroleum-based liquid fuel has dominated the transportation area till now. Also, low petroleum oil cost lessened the motivation for further technology development for alcohol fuels. Global oil shock of the 1970s are not expected to break out again within the foreseeable future, and the prospect for alcohol fuel as a remedy to soaring petroleum price is not a plausible picture either. On the other hand, clean energy generation policy by utilization of locally acquired biomass or sea algae will be emphasized to replace local consumption of liquid fuel and to produce electricity or pure alcohols for fuel cells or other means, as a rather cleaner way.

For the future energy sources, renewable-based energy society must be the final goal to reach, but unfortunately it takes a long time to reach the economics and technological easiness to be a common practice, which appears to take at least one or two decades. In order to bring the technology in earlier time, there exist many hurdles and require efforts in scientific and societal side.

All in all, future energy generation direction had been solidly established as "to be clean, renewable, and sustainable," but low petroleum cost lessened the necessity of alternative clean energy source development, e.g., alcohol fuels.

Recently, global warming is becoming a central social issue attracting worldwide attention and provides a kind of consensus that society should be changed to deal with alleviating the prime causes of $CO_2$ evolution in addition to pollution-related issues such as fine dust. The utilization of alcohol fuels reduces carbon dioxide contents in the atmosphere, thus significantly alleviating global warming potential.

Alcohol fuels have been known as a good replacement of fossil-based liquid fuels [2]. Brazil and the United States consume alcohol fuels in the most significant proportions, and such trend will not easily change. In particular, bio-ethanol are well known for its use in Brazil as a gasoline supplement (**Figure 1**).

When we say alcohol fuels, they comprise of methanol, ethanol, ethers (MTBE, ETBE, TAME, TAEE, and DME and DEE), and esters (biodiesels: methyl and

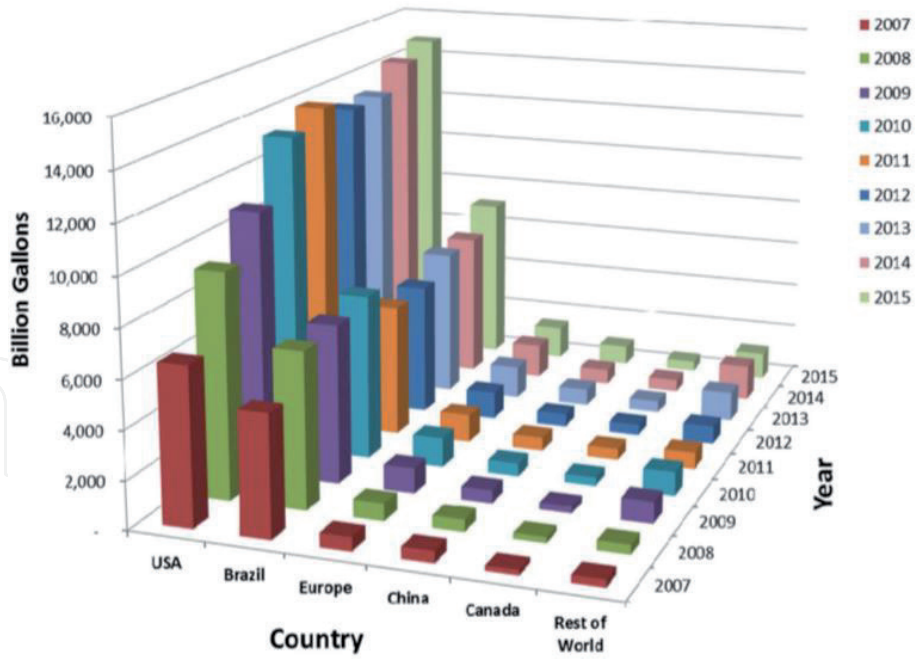


**Figure 1.**
*Worldwide ethanol production by country and year 2007–2015 [3].*

ethyl esters of fatty acids derived from vegetable oils and animal fat), in a broad sense. Most widely used alcohol fuels typically include methanol, ethanol, and bio-butanol. Ethanol that is produced through yeast-based fermentation using corn or sugarcane is the most well-known. Bio-butanol is capable of overcoming technological limitations surrounding bio-ethanol, and it is currently becoming another promising focal issue of clean energy.

The chapter deals with the current status of alcohol fuels and tries to elaborate the future direction for more wider utilization and the possible roles of alcohol fuels in attaining the far-reaching goal of low-carbon economy using sustainable energy resources.

## 2. Properties of alcohol fuels

Alcohols and ethers can replace gasoline and oil. **Table 1** exhibits properties of n-butanol, ethanol, and gasoline for comparison. In **Table 1**, RON, MON, and RVP values for butanol and ethanol are meant for gasoline blend fuels.

**Table 2** contains a more wide range of properties of alcohols and ethers compared to gasoline and fusel oil. Fusel oil or fusel alcohol is defined as a mixture of several alcohols produced as a by-product of alcoholic fermentation.

In general, alcohols contain higher values than gasoline in oxygen content, octane number, and autoignition/flash point temperatures, while freezing point temperature is lower.

Tetraethyllead has been banned for use as an additive to improve octane number of gasoline fuel. Methyl tertiary-butyl ether (MTBE) and alcohols are thus used as alternative additives to gasoline, but MTBE has also been banned after the 2000s, and alcohols have become useful additives to increase octane number of gasoline.

Water solubility of alcohols is an important property when alcohols are being used as fuel. Gasoline has a water solubility value of less than 0.01, whereas ethanol exhibits a full miscibility as 100. When alcohols contain a high solubility in water, spill or leakage of the mixed alcohol fuels can cause polluting the underground water.

| Item | n-Butanol | Ethanol | Gasoline |
|---|---|---|---|
| Specific gravity @ 60°F | 0.814 | 0.794 | 0.720–0.775 |
| Heating value, MJ/L | 26.9–27.0 | 21.1–21.7 | 32.2–32.9 |
| Research octane number (RON) | 94 | 106–130 | 95 |
| Motor octane number (MON) | 80–81 | 89–103 | 85 |
| Reid vapor pressure (RVP) of 5 and 10% Alcohol/gasoline blends, psi | 6.4/6.4 | 31/20 | <7.8/15 (summer/winter) |
| Oxygen, wt% | 21.6 | 34.7 | <2.7 |
| Water solubility at 25°C, % | 9.1 | 100.0 | <0.01 |

**Table 1.**
*Properties of n-butanol and ethanol with gasoline [4].*

| Item\fuel | Gasoline | Butanol | Methanol | Ethanol | MTBE | DME | Fusel oil |
|---|---|---|---|---|---|---|---|
| Chemical formula | $C_{5-10}H_{12-22}$ | $C_4H_{10}O$ | $CH_3OH$ | $C_2H_5OH$ | $C_5H_{12}O$ | $CH_3$-O-$CH_3$ | $C_5H_{12}O$ |
| Molecular weight | 106.22 | 74.12 | 32.04 | 46.7 | 88.15 | 46.07 | 76.42 |
| Carbon, mass% | 87.5 | 64.91 | 37.5 | 52.2 | 66.1 | 52.2 | 54.8 |
| Hydrogen, mass% | 12.5 | 13.49 | — | 34.7 | 13.7 | 13 | 15 |
| Oxygen, mass% | 0 | 21.6 | 49.93 | 34.7 | 18.2 | 34.8 | 30.32 |
| Density, g/ml | 0.737 | 0.810 | 0.792 | 0.785 | 0.74 | 0.661 | 0.847 |
| Boiling temperature, °C | 27–225 | 117.25 | 78 | 78.25 | 52.2 | −25.1 | 53.4–54.4 |
| Reid vapor pressure, Kpa | 53–60 | 18.6 | 32.4 | 17 | 54.47 | — | — |
| Research octane no. | 90–100 | 98 | 108.7 | 108.6–110 | 118 | — | 106.85 |
| Motor octane no. | 82–90 | 78 | 86.6 | 92 | 102 | — | 103.72 |
| Low heating value, MJ/kg | 44.0 | 33.2 | 20.1 | 26.9 | 34.9 | 28.8 | 29.536 |
| Freezing point, °C | −40 | — | −97.5 | −114 | −108 | — | −52 |
| Viscosity, $mm^2/s$ | 0.5–0.6 | — | 0.596 | 1.2–1.5 | 0.35 | — | 0.61 |
| Flash point, °C | −45 to −13 | — | 11 | 12–20 | −25.5 | — | — |
| Autoignition temperature, °C | 257 | 385 | 423 | 425 | 435 | 253 | 41.6 |

**Table 2.**
*Detailed properties of alcohols, ethers, and related fuels [3].*

Methanol, ethanol, and propanol are completely miscible in water, which means that they dissolve in water in any amount. Both methanol and ethanol dissolve readily in water, are fortunately biodegradable, and do not bioaccumulate. They are not rated as toxic to aquatic organisms [5].

Starting with the four-carbon alcohol (butanol), solubility is starting to decrease, and from the seven-carbon length heptanol, alcohols are practically immiscible in water (**Table 3**) [6]. This is one of the backgrounds for the development of butanol as another alcohol fuel.

Other important properties of alcohol fuels reside in its inherent swelling of plastics and corroding power for metals. These properties ask modification in the existing infrastructure of automobiles and other appliances.

| Alcohol name | Chemical formula | Water solubility |
|---|---|---|
| Methanol | $CH_3OH$ | Miscible |
| Ethanol | $C_2H_5OH$ | Miscible |
| Propanol | $C_3H_7OH$ | Miscible |
| Butanol | $C_4H_9OH$ | 0.11 |
| Pentanol | $C_5H_{11}OH$ | 0.03 |
| Hexanol | $C_6H_{13}OH$ | 0.0058 |
| Heptanol | $C_7H_{15}OH$ | 0.0008 |

**Table 3.**
*Alcohol solubility in water in mol/100 g of $H_2O$ (1 bar, 25°C) [6].*

### 2.1 Ethanol

Ethanol is a clear, colorless, toxic liquid and has a characteristic odor. Ethanol is not classified as toxic to humans. Ethanol has a higher octane number than gasoline, providing premium blending properties as a liquid fuel. Ethanol contains less energy per volume than gasoline, and denatured ethanol (98% ethanol) contains about 30% less energy than gasoline per volume [7]. Since ethanol contains oxygen, using it as a gasoline additive results in up to 25% fewer carbon monoxide emissions than conventional gasoline [8].

Ethanol is soluble in polar and nonpolar solvents and has a clearly higher vapor pressure than gasoline and an oxygen content of approximately 35%. Ethanol itself is a good solvent and can be mixed with water in unlimited quantities. Because ethanol is a short-lived compound in surface water and subsurface aquifer, substantially limiting the risk to aquatic organisms, environmental problem is minimal even when it is spilled. Ethanol degrades quickly in the natural environment, and the biodegradation is rapid in soil, groundwater, and surface water, with predicted half-lives ranging from several hours to 10 days [9].

### 2.2 Methanol

Methanol, or wood alcohol, is a colorless, odorless, toxic liquid and is the simplest form ($CH_3OH$) among alcohols [8]. Methanol is corrosive to some materials. Methanol can be produced from several sources: synthetic gas (syngas), formic acid, formaldehyde, and methane. Methanol is classed as toxic so it requires additional considerations during usage to limit inhalation exposure and skin contact.

Methanol is hygroscopic, meaning that it will absorb water vapor directly from the atmosphere. Because absorbed water dilutes the fuel value of the methanol and may cause phase separation of methanol-gasoline blends, containers of methanol fuels must be kept tightly sealed [10].

### 2.3 Butanol

Butanol has higher energy densities and could be distributed in the existing infrastructure [8]. The use of ethanol as an additive to gasoline to increase octane number has downside effects such as corrosion of metal component and vapor lock. Such troubleshooting can be remedied by modification of engine and fuel system, but addition of alcohols with high carbon number such as bio-butanol enables utilization in existing system without rendering any change.

Alcohols with high carbon contents such as butanol can be synthesized from syngas through catalytic reaction that employs modified catalysts used in Fischer-Tropsch or methanol synthesis.

## 3. Feedstock for alcohol fuels

Alcohols fuels can be made from all available organic materials. Natural gas, coal, biomass, and organic wastes are good sources. Alcohol fuels have been synthesized from corn and sugar cane as major raw materials, but focal issues nowadays are synthesis and production of alcohol fuels from non-food crops and agricultural residues. Non-food lignocellulosic biomass includes energy crops, cellulosic residues, and wastes.

Grain-based ethanol as a first generation has been tried to change to the second-generation cellulosic ethanol and other advanced cellulosic biofuels. Cellulosic ethanol has identified as a key biochemical route of converting biomass to fuels after the 2000s [8]. Algae-based third-generation feedstock for alcohol fuels emerged as a candidate that can provide a vast raw material for future alcohol fuel industry. **Figure 2** illustrates the generations of raw feedstock for the alcohol fuel production and also shows the most apparent material that is being utilized in different countries.

Definitely there exists a clear difference between developing countries and developed countries in the priority choice, but basic understanding should be identical: use the locally available, underutilized feedstock, and choose the feedstock that tipping fee is available to treat the feedstock like municipal/industrial wastes. However, when wastes are involved as feedstock, it should be noted that not-in-my-backyard (NIMBY) problem occurs as a norm in almost every countries nowadays.

The European Commission has recently resolved by voting against utilization of biofuels synthesized from biomass of food crop sources by the year 2030. Intensive interdisciplinary efforts are anticipated for timely commercialization of cellulosic bio-ethanol, which is the second-generation bio-alcohol.

Agricultural waste typically contains a relatively high content of alkali metals (potassium and sodium) and other inorganic elements including calcium, magnesium, and sometimes chlorine and sulfur. When applying thermal methods in

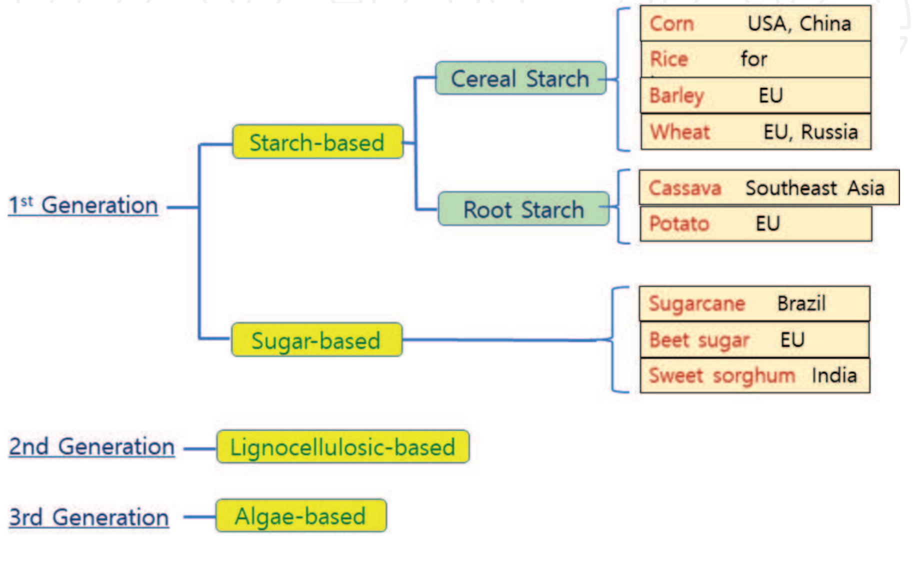


**Figure 2.**
*Key raw materials for bio-ethanol production in different countries (modified figure from Ref. [11]).*

converting these wastes to alcohol fuels, alkali metal components act to produce low-melting salts that will cause plugging and other ash-related problems during the process. In contrast, fermenting method can reduce the tendency of ash problems, which is a beneficial aspect in actual manufacturing process.

In particular, rice husk contains ash content of over 90%, and rice straw consists of more than 30% as silica, although there is a variation with rice stock, climate, and geographical environment. Such inorganic contents work as a barrier to thermal conversion process, and fermenting can be a more appropriate way in converting this biomass feedstock.

### 3.1 First generation: grain feedstock

Starch and carbohydrates have been used as a first-generation raw material to produce ethanol. During the year 2013, more than 90% of bio-ethanol had been produced from the starch and carbohydrates. Corn, grain, and cassava are major such crops. Downside issues are the destruction of environment during the crop cultivation and ethanol production as well as the use of valuable food resources as fuel production. Therefore, at current situation, large agricultural countries like the United States, Brazil, and China are major production places of biofuels including alcohol fuels. In the United States, 95% of ethanol has been produced from the starch in corn grain [7].

### 3.2 Second generation: lignocellulosic biomass

Recently, the production of bio-ethanol from grain-based raw materials is gradually becoming limited, and the second-generation bio-ethanol production from non-grain-based biomass is now receiving a gradually increasing priority.

Bio-ethanol is currently becoming a solid option as automobile fuel, and it has been usually produced from starch of corn and cassava or sugary contents of sugar cane and sugar turnip. Bio-ethanol is also produced from lignin cellulose-based material of crop wastes. Sugar and starch are readily convertible to bio-ethanol but their availability is limited and they are costly. Therefore, work is underway to investigate into various processes to produce bio-ethanol from lignocellulose-based raw materials to utilize their abundant amount in nature and to meet the economic viability in the market [11]. Wood chips or crop residues are common lignocellulosic feedstock (**Figure 3**).

Non-edible xylem parts that constitute most of the botanical stocks or cellulose are used to produce ethanol. Rice straws, weeds, and other shrubbery are good examples as raw material for alcohol production, and valuable food resources are not wasted in this case. However, a large-scale forest or farmland is still used and the low-production efficiency is a problem. Also, economically, viability is not satisfactory yet and is not applied at measurable proportion [13].

The main obstacle of using lignocellulosic biomass resides in the difficulty in extracting the essential parts from the hard-binding components of lignin, hemicellulose, and cellulose in plants as shown in **Figure 3**.

High-growth productivity of lignocellulosic crops compared to corn and sugarcane is one of the key factors that bio-alcohols can be produced economically in the future. **Figure 4** clearly shows the high growth rates in lignocellulosic crops like sorghum, energy cane, and water hyacinth.

### 3.3 Third generation: algae species

Sea algae grow relatively faster than most of the land-based plants as shown in **Table 4**, and they are good source of raw material to produce alcohol fuels.

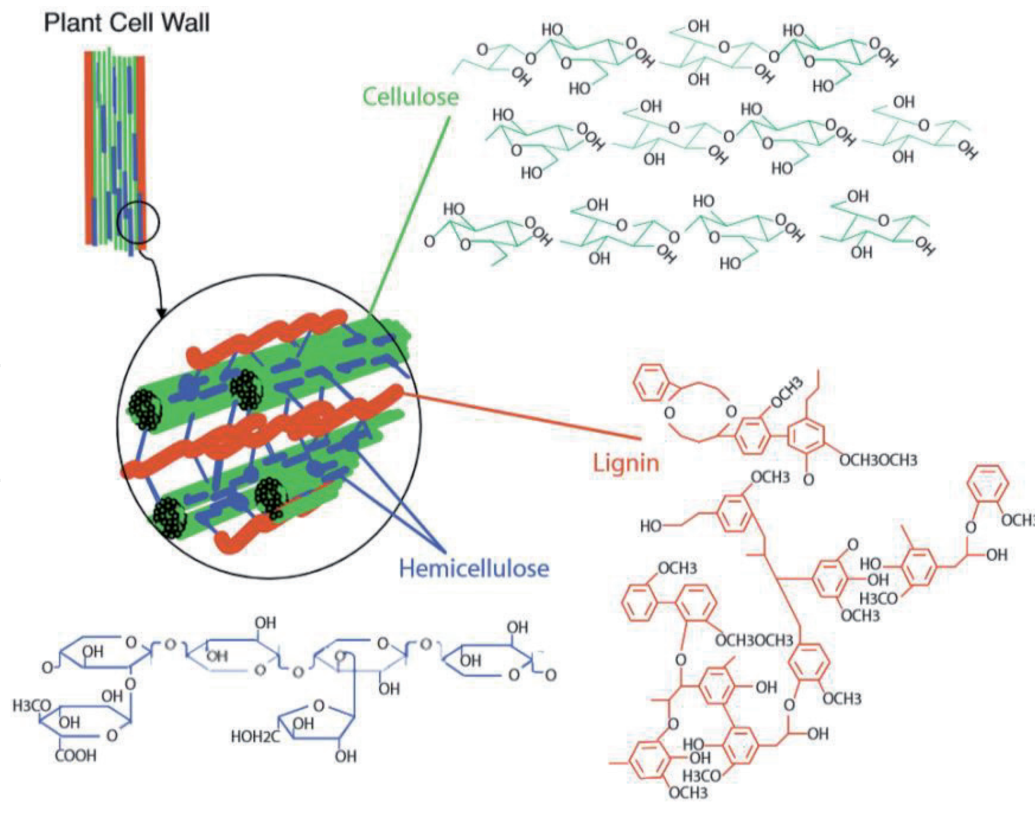


**Figure 3.**
*Three key components of lignocellulose [12].*

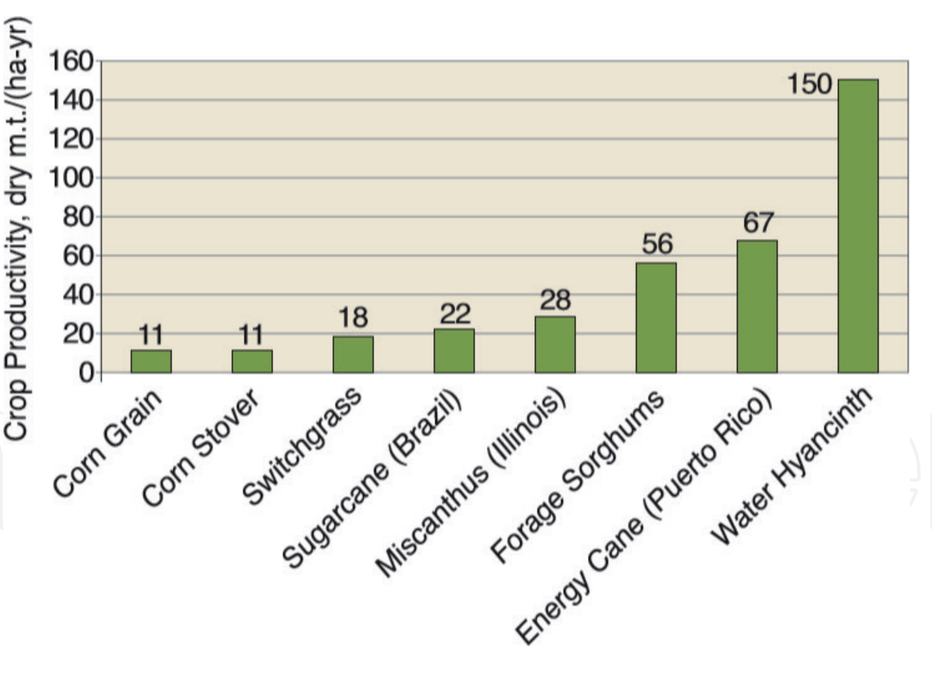


**Figure 4.**
*High-growth productivity of lignocellulosic crops to corn and sugarcane [12].*

They do not require large-scale farmland to cultivate, and non-edible algae are also a good source of bio-ethanol. Due to their fast growth rate, large-scale farming for 4–6 times cropping per year is possible and their carbon dioxide sequestration is 3–7 times more effective than that of grains. However, large-scale acquisition of the raw sea algae and its economic viability remains to be overcome before commercialization. Most of algae-related efforts are still under R&D probing stage.

Fundamental background to try algae species for biofuel production relies on their higher efficiency in converting solar energy than higher plant biomass.

| Oil Yields | Litre/Hectare/Year | Barrels/Hectare/Year |
|---|---|---|
| Soybeans | 400 | 2.5 |
| Sunflower | 800 | 5 |
| Canola | 1,600 | 10 |
| Jathropha | 2,000 | 12 |
| Palm Oil | 6,000 | 36 |
| Microalgae | 60,000 – 240,000 | 360 – 1,500 |

**Table 4.**
*Current biofuel yields from various biomass [14].*

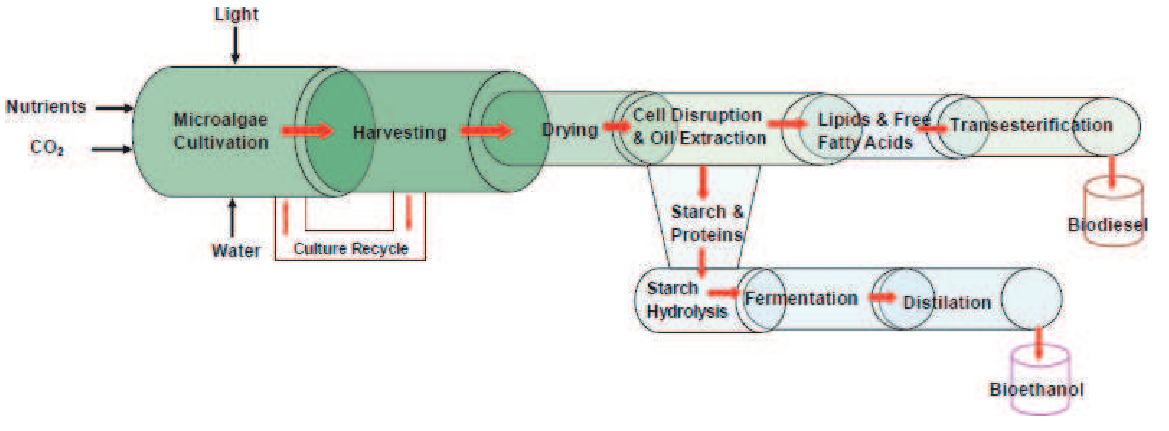


**Figure 5.**
*Biofuel production sequence from microalgae [14].*

However, actual cultivation of microalgal biomass is not easy, rather quite challenging and still expensive than growing crops. It is a similar situation as comparing the product that has been updated for several decades and the one that is starting to experience initial trial and errors.

**Figure 5** illustrates the typical biofuel production procedures in which the basic process is identical with the hydrolysis/fermentation/separation parts of bio-ethanol production, except the feedstock cultivation and harvesting parts.

## 4. Manufacturing processes

Ethanol can be produced in various ways: syngas from coal and biomass, synthesized from petroleum-based ethylene, or by fermentation of sugary contents. Bio-ethanol is produced through the procedures of fermentation of regenerative biomass, distillation, and purification.

Sugar canes and corns are mainly used to produce bio-ethanol in Brazil and the United States, respectively. Overall manufacturing process for bio-ethanol composes the following key parts: pretreatment, saccharification (hydrolysis), fermentation, and purification as shown in **Figures 6** and **7**.

Ethanol is mainly made by fermenting the sugars found in grains, such as corn and wheat, as well as potato wastes, cheese whey, corn fiber, rice straw, urban wastes, and yard clippings. There are several processes that can produce alcohol (ethanol) from biomass. The most commonly used processes today use yeast to

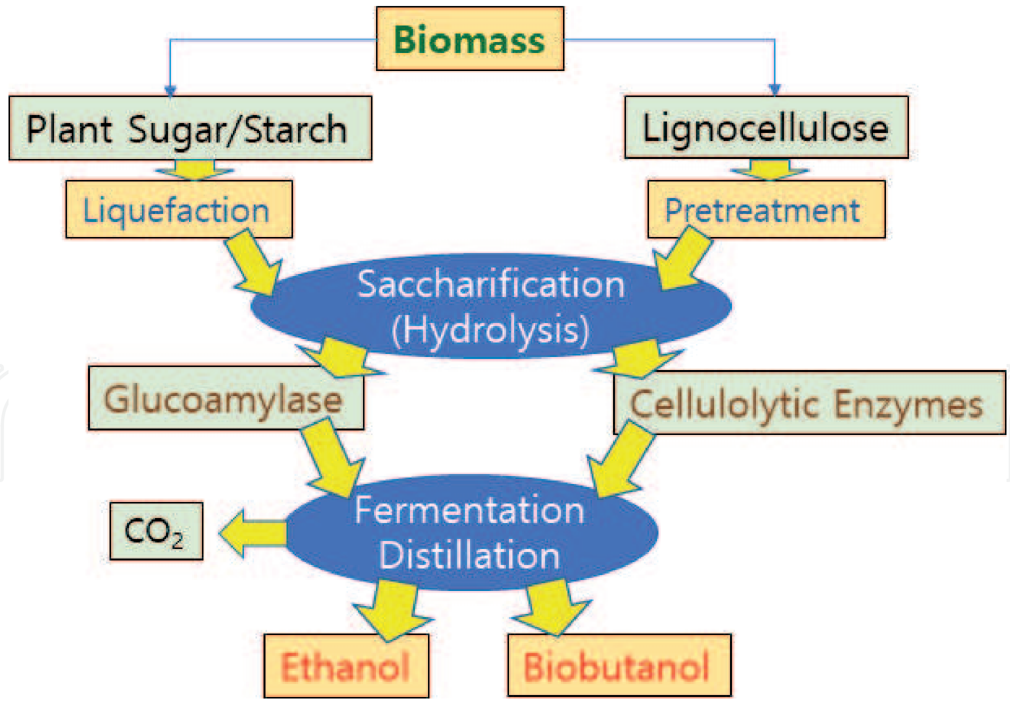


**Figure 6.**
*Steps involved in biochemical conversion of biomass to alcohol fuels (modified from Ref. [8]).*

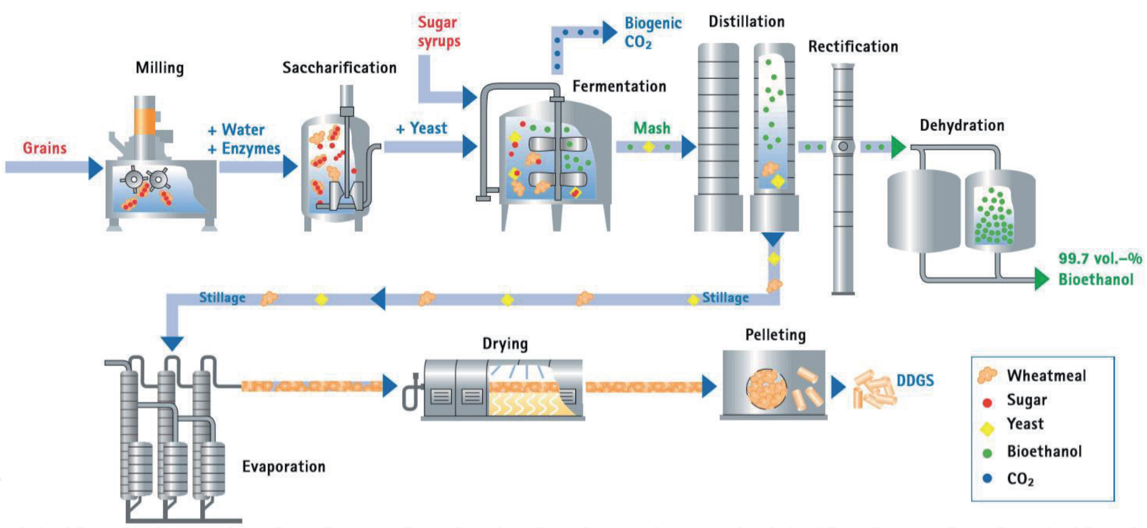


**Figure 7.**
*Schematic flow diagram of bio-ethanol production process [15].*

ferment the sugars and starch in the feedstock to produce ethanol. Another process uses enzymes to break down the cellulose in woody fibers, making it possible to produce ethanol from trees, grasses, and crop residues [8].

Synthesis of ethanol as a sustainable source of energy, especially related to more high-end product form of alcohol with high carbon contents, requires the accumulation of technical know-how in preparation for future depletion of petroleum oil resources. The bio-alcohol production process is shown in schematic flow diagram for bio-butanol manufacturing in **Figure 8**.

### 4.1 Pretreatment

Recently, the conversion of valuable food resources into alcohol fuel is facing very negative criticism worldwide, and work is underway to switch the raw material for bio-ethanol to non-edible biomass. However, the production of bio-alcohol

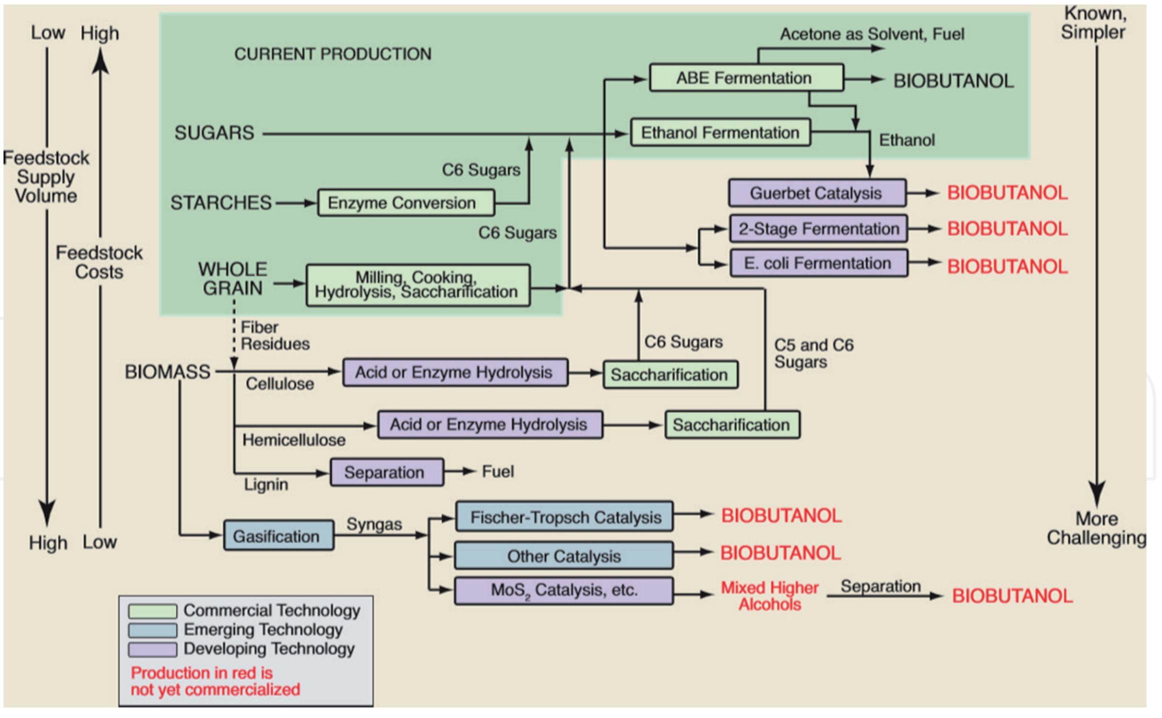


**Figure 8.**
*Schematics of bio-butanol production process [4].*

from non-edible cellulosic biomass requires solving the problem of breaking the hard biomass structure before converting into alcohol fuels. Pretreatment step is important. The pretreatment process is costly since it involves several process steps and costs for enzymes. It is very important to develop the low-energy/energy-saving process scheme and the suitable enzyme to overcome such technical/cost barriers.

The first challenge in the conversion of biomass to alcohol fuels starts with the difficulty in breaking down the recalcitrant structure of biomass cell walls and further breaking down the cellulose to 5–6 carbon sugars that can be fermented by microorganisms [8]. Size reduction and uniformization in density/size are the first preparation step. Pretreatment by steam, hot water, or slight carbonization is a common procedure.

Various ways of pretreatment are used in biomass conversion to alcohols as illustrated in **Table 5**. Recent types include steam explosion auto-hydrolysis, wet oxidation, organosolv, and rapid steam hydrolysis (RASH) [16]. Organosolv is a pulping technique that uses an organic solvent to solubilize lignin and hemicellulose. The principal purpose of most pretreatment is to increase the susceptibility of cellulose and lignocellulose parts of biomass at the next process in which acid and enzymatic hydrolysis occur. Cellulose enzyme systems react very slowly with un-pretreated biomass, whereas the rates of enzymatic hydrolysis enhance dramatically when the lignin barrier around the plant cell is partially disrupted [16].

### 4.2 Saccharification (hydrolysis)

Saccharification is basically a step of breaking down the cellulose/hemicellulose through hydrolysis to make sugars such as glucose and xylose. The overall hydrolysis is based on the synergistic action of three distinct cellulase enzymes depending on the concentration ratio and the adsorption ratio of the component enzymes (endo-beta-gluconases, exo-beta-gluconases, and beta-glucosidases) [16].

Two main procedures exist in hydrolysis: acid hydrolysis and enzymatic hydrolysis. Most commonly employed procedure is the enzymatic one because it has a

| | Residence Time | Temperature | Pressure | Other Conditions |
|---|---|---|---|---|
| **Chemical** | | | | |
| *Acid-Catalyzed* | | | | |
| Autohydrolysis | ~1 h | ~200°C | ~15 atm | |
| Steam Explosion | 0.3–50 min | 190–250°C | 12–40 atm | |
| Liquid Hot Water | 2–15 min | 190–220°C | 13–25 atm | |
| Liquid Hot Water (Neutral pH) | ~15 min | 160–220°C | 6–25 atm | |
| Dilute Acid ($H_2SO_4$, $SO_2$, HCl, $HNO_3$) | 5–30 min | 140–190°C | 4–13 atm | 0.5–10% Acid |
| Concentrated Acid ($H_3PO_4$) | 30–60 min | 0°C | 1 atm | 85% $H_3PO_4$ |
| Peracetic Acid ($C_2H_4O_3$) | 1–180 h | 25–75°C | 1 atm | 2–10% $C_2H_4O_3$, 0.2–1.0 g $C_2H_4O_3$/g biomass |
| Supercritical Carbon Dioxide | 1 h | 35–80°C | 70–270 atm | |
| *Base-Catalyzed* | | | | |
| Sodium Hydroxide | 24–96 h | 25°C | 1 atm | 1% NaOH, 0.1 g NaOH/g biomass |
| Lime ($Ca(OH)_2$) | | | | |
| Low Lignin Content (12–18%) | 1–2 h | 100–120°C | 1–2 atm | 0.10 g $Ca(OH)_2$/g biomass |
| Medium Lignin Content (18–24%) | ~30 days | ~55°C | 1 atm | 0.10–0.15 g $Ca(OH)_2$/g biomass |
| High Lignin Content (>24%) | ~2 h | ~150°C | 15 atm | 0.15–0.20 g $Ca(OH)_2$/g biomass |
| Wet Oxidation | 15 min | 185°C | 12 atm | 0.6% $Na_2CO_3$ |
| Ammonia ($NH_3$) | | | | |
| ARP | ~15 min | ~180°C | ~20 atm | 15% $NH_3$ |
| AFEX | ~5 min | 60–100°C | ~20 atm | 1 g $NH_3$/g biomass |
| Oxidative Alkali (NaOH + $H_2O_2$ or $O_3$) | 6–25 h | 20–60°C | 1 atm | 1–15% $H_2O_2$ or $O_3$, pH = 11.5 |
| *Solvents* | | | | |
| Organosolv | 60 min | 180°C | 35–70 atm | 1.25% $H_2SO_4$, solvent = 60% ethanol |
| Cellulose Solvents | Generally not viable for industrial applications | | | |
| **Physical** | | | | |
| Comminution | Does not significantly improve digestibility | | | |
| Ball Milling | Not economically viable | | | |
| Compression Milling | Not economically viable | | | |
| Radiation | Not economically viable | | | |

**Table 5.**
*Pretreatment technologies currently available for alcohol fuels [12].*

better environmental and economic performance. Acid hydrolysis operates under severe conditions of high temperature and low pH, which results in corrosive conditions and requires a special construction material [17].

### 4.3 Fermentation

Fermentation is the biological process using microorganisms to convert sugar and starch into ethanol. The production of bio-ethanol from starch-containing cereals typically includes the following five steps [15]:

1. Milling, which is the mechanical crushing of the cereal grains to release the starch components
2. Heating and addition of water and enzymes for conversion into fermentable sugar
3. Fermentation of the mash using yeast, whereby the sugar is converted into bio-ethanol and CO2
4. Distillation and rectification, which is a step of concentrating and cleaning the ethanol produced by distillation
5. Drying (dehydration) of bio-ethanol

In Brazil, bio-ethanol is produced from sugar cane. Sugar cane is a sugar-bearing crop, and it is readily converted into ethanol by fermentation with yeast. Harvested sugar cane is thoroughly washed and crushed into pieces, the juice is extracted, and finally it is converted into sugary juice, which is further fermented by yeast. During the process, hydrous alcohol is produced by non-dehydration process and anhydrous one by dehydration process. Anhydrous ethanol is mixed with gasoline for the prevention of phase separation, and hydrous alcohol is used as fuel for all kinds of vehicles. The process wastes during the washing and crushing are again utilized as a boiler fuel to generate steam and electricity for subsequent ethanol production. In addition, for each ton of bio-ethanol, 1 ton of GMO-free, high-protein animal feed can be produced.

### 4.4 Comparison between SSF and SHF processes

Cellulose hydrolysis and fermentation can be achieved through two different process schemes, depending on where the fermentation occurs: separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) [16].

In SHF, hydrolysis is performed in one reactor and the hydrolysates are fermented in the next second reactor. In SHF, feedstock and utility costs are high due to the cellulosic conversion that shows only about 73% to ethanol in 48 hours, while the remainders are burned. In SSF, hydrolysis and fermentation are carried out in a single reactor, and the operating cost is in general lower than the SHF case. In SSF, yeast ferments the glucose into ethanol as soon as the glucose is produced, which results in preventing the sugars from accumulating/inhibiting the final product.

The SSF system offers a large advantage over SHF processes, because of their reduction of final product inhibition of the cellulase enzyme complex [16]. The SSF process shows a higher yield (88 vs. 73%) and greatly increases product concentrations (equivalent glucose concentration, 10 vs. 4.4%). The most significant advantage is that enzyme loading can be reduced from 33 to 7 IU/g-cellulose, which results in lowering the ethanol cost significantly.

A hybrid hydrolysis and fermentation (HHF) process is also proposed in converting lignocellulosic biomass into ethanol. This process configuration begins with a separate hydrolysis step which involves a higher temperature enzymatic cellular saccharification and ends with SSF step which involves a simultaneous step of mesophilic enzymatic hydrolysis and sugar fermentation.

## 5. Utilization of alcohol fuels

About 66% of worldwide ethanol products are used for transportation purpose and 21% goes to industrial use. Most widely used area is gasohol in that alcohols are mixed to replace a portion of gasoline. In the near future, alcohol-using fuel cells and alcohol-mixed jet fuels are promising area of application.

**Figure 9** shows the ethanol consumption trend for mixing to gasoline in the United States during the period of 1980–2020. During the years 2005–2010, ethanol use has drastically increased and remains as ca. 10% of the total gasoline consumed amount.

### 5.1 Fuel for automobiles

The most abundant application of alcohol fuels is related to internal combustion engine of automobiles. Mixing alcohol fuels into gasoline has also a purpose of reducing pollutants by oxygenating the fuel. Since methanol is less expensive

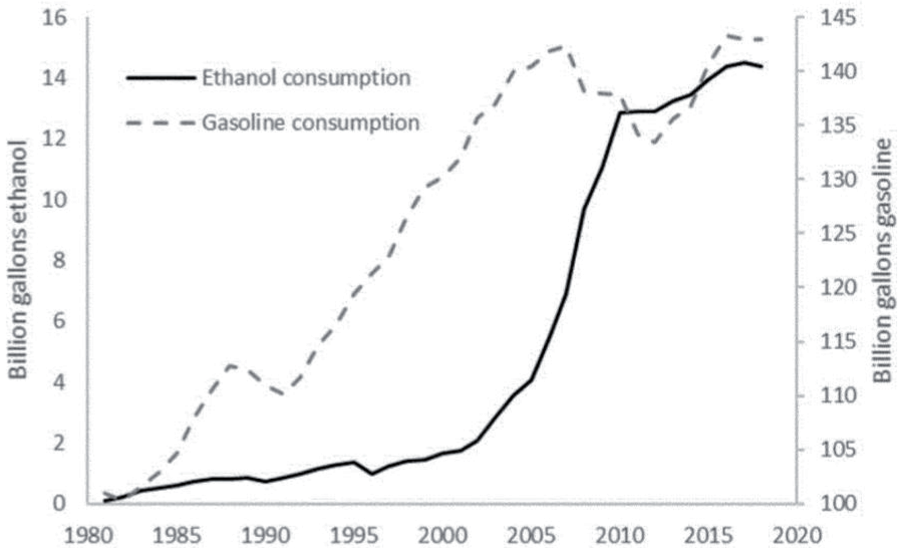


**Figure 9.**
*Trend of alcohol additive consumption for gasoline in the United States [18].*

| Country | Ethanol program |
|---|---|
| Brazil | Mandatory of bio-ethanol proportion as mixture of 24 ± 2% |
| United States | 10% target for bio-ethanol proportion among primary energy sources (2010) |
| EU | Biofuel proportion increase to 2% in 2005, to 5.75% in 2010 |
| Canada | Mandatory of bio-ethanol proportion in fuel set at 10% |
| China | Mandatory mixing of bio-ethanol at regional government level |
| India | Current mandatory 5% mixing of bio-ethanol and to be increased to 20% |
| Columbia | 10% bio-ethanol to be mandatory at metropolitan area |
| Thailand | 10% mandatory mixing of bio-ethanol to be enforced within Bangkok area |
| Argentina | 5% bio-ethanol to be mandatory |

**Table 6.**
*Ethanol mixing program to gasoline in different countries [11].*

to produce than ethanol, although methanol is generally more toxic and has lower energy density than ethanol, it has been used with ethanol as automobile fuels. Compared to gasoline, methanol and ethanol have characteristics of burning at lower temperatures and lower volatility, which results in difficulty in starting the automobile engine in cold weather.

Current alcohol mixing status of ethanol-based fuel utilization in different countries is tabulated in **Table 6**.

Currently, flexible fuel vehicle (FFV) with dual fuel supply system for ethanol and gasoline is commercialized and widely distributed. In the case of methanol blending to gasoline, it is limitedly used in China from the 2000s. In China, M15 (15% methanol/85% gasoline) is the most familiar type [19].

Low-molecular weight alcohols such as ethanol have replaced conventional octane boosting additives like MTBE in automobile fuels. Alcohols that are added to gasoline make the mixed fuel to combust more completely by acting of higher oxygen content by alcohols and provide the ensuing effects of higher combustion efficiency and lower air pollution emissions [20].

In the United States, bio-ethanol is mandatorily mixed with transportation fuels. It has been reported that the bio-ethanol policy reduced crude oil reliance to 25%

from 60%, and simultaneously creating 400,000 jobs, reducing 43% in greenhouse gas generation and cost-saving effect of $1.5/gallon-gasoline to the consumer [13].

Small amounts of methanol and higher alcohols are also allowed to be blended into gasoline within EN228 limits. E85 is used in FFVs in certain areas within the EU (such as Sweden, France, and Germany) [21]. There was a trial to use a near-neat fuel as M85 which contains 85% methanol/15% gasoline.

Racing cars used methanol for a long time, mainly by not producing black smoke which otherwise will block the view of ensuing other racing cars. Other than this application to racing cars, methanol fuel has not applied widespread other than some experience in China, methanol programs in California during the 1980–1990s, and a trial in Sweden as a marine fuel.

More than 98% of US gasoline contains typically 10% ethanol as E10 (10% ethanol/90% gasoline) [7]. Flexible fuel automobiles that can use E85 (85% ethanol/15% gasoline) exist in the United States and Brazil.

In Brazil, 95% of automobiles are using fuel-flex engine system. Around 70% of automobiles in Brazil are able to run on ethanol, and the Brazil's demand for ethanol is estimated to increase by around 70% by 2030 (**Figure 10**) [1, 22].

As for bio-butanol, the commercial scale production facility has not been constructed in sufficient numbers. In the United States, bio-butanol can be mixed up to 12.5%, and the 16% mixture is reported to be equivalently effective to existing E10 [13].

Ethers such as dimethyl ether (DME) contain oxygen in chemical structure which acts as an oxidant in minimizing soot formation. Other exhaust emissions such as unburned hydrocarbons, NOx, and particulate matter are also reduced [8]. DME is an ultra-clean fuel that has similar properties to LPG.

### 5.2 Fuel cells

Alcohol fuel cell is an energy conversion device to generate electricity via electrochemical reactions on the catalytically active electrodes without direct combustion of alcohol fuel. Direct alcohol fuel cell (DAFC) is named for its direct supply of alcohol to fuel electrode and is called with specific terminologies as direct methanol fuel cell or direct ethanol fuel cell depending on the alcohol fuel source.

The mechanism of electricity generation is based on the oxidation of methanol fuel at the anode (fuel electrode) and conduction of electron(s) to the cathode (air or oxygen electrode) via external conducting circuit and simultaneous electrolytic conduction of proton ($H^+$) via polymer electrolyte to the cathode.

DAFC can provide portable energy source to electronic devices such as cellular phones and notebook computers [23]. DAFC that uses alcohol can have several

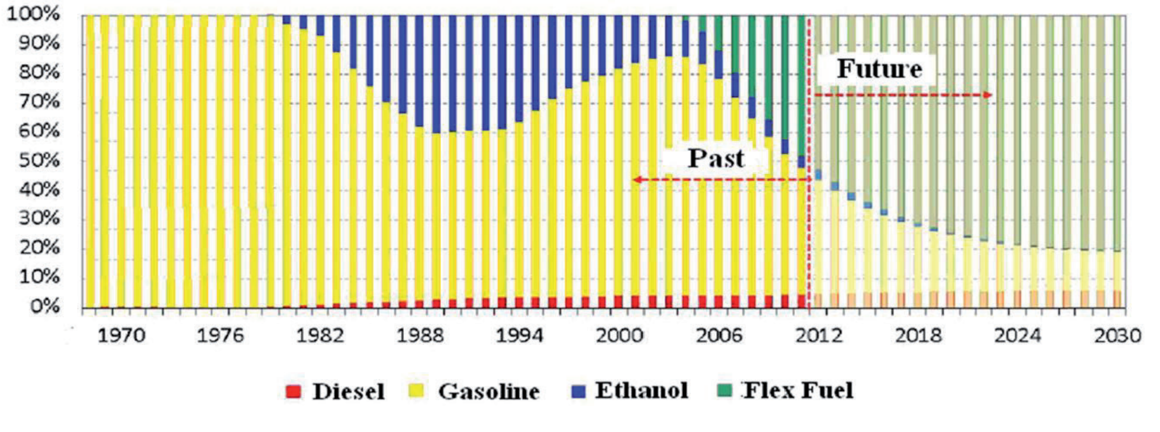


**Figure 10.**
*Changing trend of automobile fuel in Brazil [22].*

advantages in terms of storage, transportation, safety, etc. over fuel cell systems like proton exchange membrane fuel cell (PEMFC) that use hydrogen.

### 5.3 Jet fuel

Alternative jet fuel typically contains a complex mixture of primarily n/iso-paraffins, cycloparaffins, and alkylbenzenes with a carbon number range of 9–15 [24]. Carbon tax accelerates the development of jet fuel from renewable resources. Lowering emissions of particles and greenhouse gases during the flight are the fundamental reason of trying alcohol fuels as a jet fuel option.

Using a 50/50 (v/v) blend of petroleum-based and lipid-based jet fuels for flight was already approved by the American Society for Testing and Materials (ASTM) committee. However, the lack of raw materials and relatively low jet fuel yield of this process limit its application [24].

## 6. Environmental aspects

Global recognition regarding the significant long-term impact due to climate change provides a key foundation for utilizing alcohol fuels, which means that alcohol fuels should be able to accommodate chances in reducing climate change gases($CO_2$, methane, $N_2O$, etc.). Bio-ethanol is highly effective in reducing greenhouse gas evolution. Corn-based bio-ethanol is reported to generate 43% less greenhouse gases compared to pure gasoline.

From purely theoretical point of view, ethanol can be finally produced from the biomass that is made based on the $CO_2$ absorbed by plants during photosynthesis, and thus it can be called carbon neutral. Unlike hydrocarbons which evolve voluminous amount of $CO_2$ from their internal carbon atoms during combustion, ethanol can be regarded as carbon neutral without generating as much $CO_2$ from internal carbon atoms. In practice, however, significant amount of greenhouse gas evolution is directly and indirectly caused by cultivation of biomass crops and synthesis of alcohol fuels.

The range of $CO_2$ reduction potential is large when alcohol fuels are used. Values range between 0.5 kg $CO_2$-equivalent/liter of ethanol for ethanol produced from wheat and up to 2.24 kg $CO_2$-equivalent/liter of ethanol for ethanol manufactured from sugar cane (**Figure 11**) [25].

According to the result shown in **Figure 11**, among alternative liquid fuels, only cellulosic ethanol, biomass to liquid (BTL), and CCS-involved processes (BTL-CCS, CBFT-CCS, CBMTG-CCS) exhibit the $CO_2$-negative performance in life cycle analysis (LCA) perspective. Carbon capture and storage (CCS) process is not fully economically feasible and technically proven till now; moreover, considering public objection on CCS, connecting the process to CCS is not practical for the time being. In $CO_2$ reduction aspect, cellulosic ethanol is the most reasonable choice as a renewable alternative fuel.

Adding ethanol to gasoline fuel of automobile, oxygen contents of fuel mixture increases and yielding the effect of reducing pollutants evolution. As alcohol fuels are inherently sulfur-free, it suits for cleaner environment. Besides, since ethanol is produced by fermentation with crops that contains starch, its purity is high, and no hazardous combustion by-products such as $SO_2$ or metal oxides are generated during the combustion when compared to the petroleum-based fuel. But, high solubility into water by short carbon chain alcohols such as ethanol and methanol can cause an underground water pollution, although short carbon chain alcohols are well degradable in few days under normal circumstances. This problem can be minimized with the use of higher carbon chain alcohols like bio-butanol.

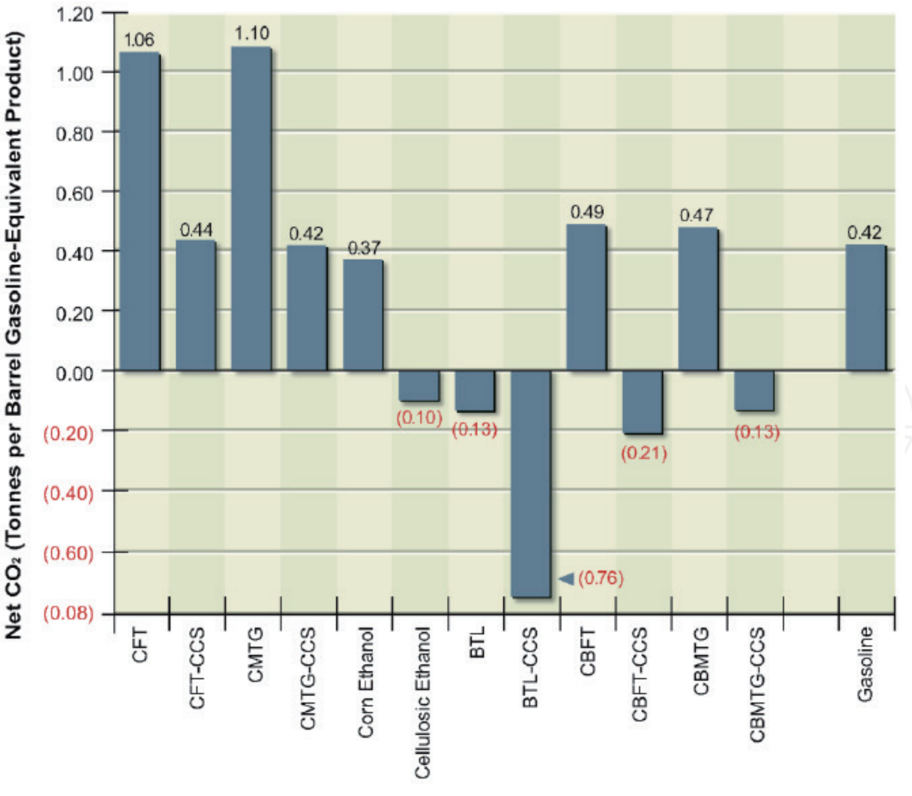


**Figure 11.**
*Estimated carbon dioxide ($CO_2$) emissions over the life cycle of alternative fuels [8, 26]. Note: BTL, biomass to liquid; CBFT, coal and biomass to liquid, Fisher-Tropsch; CBMTG, coal and biomass to liquid, methanol to gasoline; CCS, carbon capture and storage; CFT, coal to liquid, Fisher-Tropsh; CMTG, coal to liquid, methanol to gasoline.*

Forest clearing and chemical fertilizer are involved to grow corn and other grains for the first-generation bio-ethanol, which eventually ends up with $CO_2$ production and countervailing the $CO_2$ reduction amount by bio-ethanol use, sometimes more than the reduced amount. In this regard, the second-generation lignin-based or third-generation algae-based raw material is a better candidate for bio-alcohols.

It is especially noteworthy that the definition of (environment friendly) bio-energy is rather more stringently defined in the EU and United States: more than 35% reduction of greenhouse gas is required to qualify compared to fossil fuels of the same calorific value [27].

The issue of required water amount asks the approach of water-energy nexus in that technology development will follow for the process of better environment-friendliness and sustainability [13]. As an example, recent water shortage encountered in Chennai, India, might be attributable to global warming, and the water quantity consumed for the production of alcohol fuels is emerging as an important issue. Chennai region went without rain for 200 days in 2018.

The process consuming the largest amount of water is the cultivation of biomass crops. Among the production processes for alcohol fuels, refinery step consumes the largest amount of water. The water quantity consumed for US corn-based ethanol production is approximately equivalent to the water requirement that can sustain 5000 people for 1 year.

Moreover, the refinery process that is going to be extended for the second-generation cellulosic ethanol is expected to consume 2.9 times more water needed for corn-based ethanol refinery process. At present, cellulosic ethanol production process consumes about 9.8 L/L-ethanol [13], which is unduly high.

## 7. Incentive system: renewable fuel standard (RFS)

To a great extent, expanding the distribution of bio-alcohol depends on the RFS system currently implemented in many countries. Basically, biomass ethanol cannot compete in normal market situation with petroleum-based fuels. As shown in **Figure 12**, liquid fuel cost of corn ethanol and cellulosic ethanol is similar to the level of crude oil price around $90–110/barrel. Considering the crude oil price during the 2000s, this high level of biomass-based ethanol price cannot compete in normal market situation. To make a room to enter the fuel market, incentive system of renewable fuel standard (RFS) was introduced.

Important aspect in **Figure 12** is that bio-ethanol route (corn ethanol, cellulosic ethanol) is cheaper than the biomass to diesel/gasoline (BTL) route and comparable to the coal/biomass to diesel/gasoline (CBFT) route.

Mandatory addition of renewable energy sources in regulated proportions for transportation fuel is underway in 64 countries worldwide in connection with greenhouse reduction effects. Most such countries employ ethanol-based mixing program, while a few countries including Korea implement mandatory mixing of biodiesel only [13].

In the EU, 27 countries operate the mandatory mixing policy for bio-alcohol. Many countries in different continents implement similar policy: 13 nations in North and South America, 12 nations in Asia-Pacific, 11 nations in Africa and contiguous nations along Indian Ocean, and 2 nations in non-EU sphere [13]. All in all, current trend regarding bio-ethanol mixing in major countries is summarized as follows: mandatory mixing ratios are 27% in Brazil since 2015, while nine provincial governments of China mandate 10% mixing and, it will be expanded to the entire China by 2020. RFS program was newly initiated in Vietnam since 2018 for 5% ethanol mixing. Canadian E5 mandates 5% mixing and E8.5 program is implemented in five Canadian states. Columbia implemented E8 since 2008, but E5 was targeted in Chile but not mandatorily regulated. Costa Rica mandatorily implement E7 while E10 and E2 are regulated in Jamaica and Mexico, respectively. The EU currently mandates 5.75% mixing with 10% objective for 2020 and recommends EU member nations to accomplish target 10% ratios of 2020 [13].

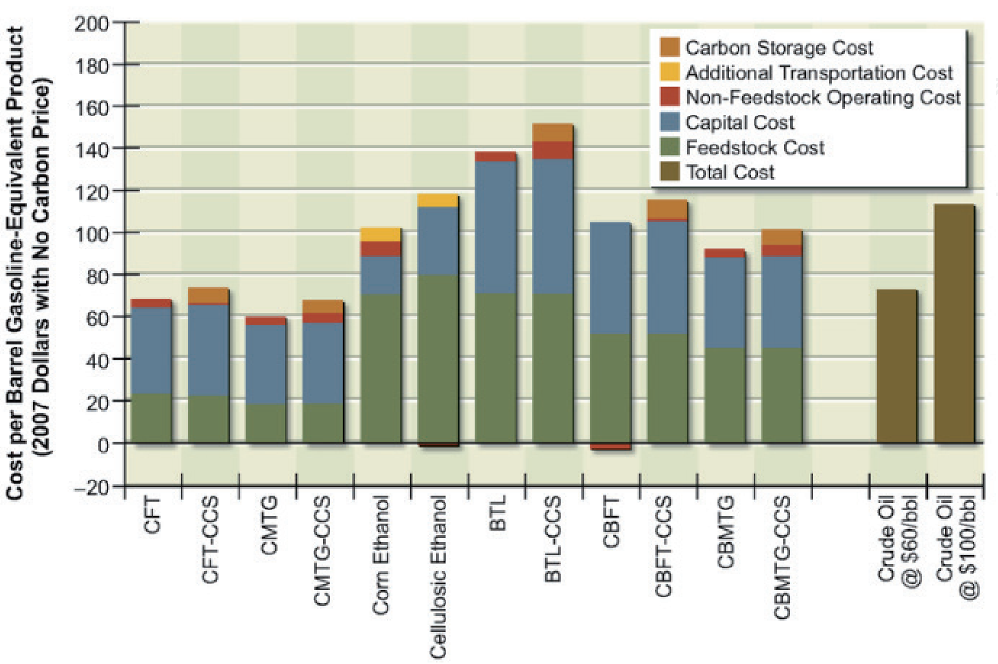


**Figure 12.**
*Costs of alternative liquid fuels of different origins with zero carbon price [8, 26].*

In the United States, MTBE additive to transportation fuel was gradually becoming prohibited since 2002 to prevent the groundwater pollution, and 25 US states had banned the use of MTBE by 2007. Bio-ethanol has thus become a replacement for MTBE. Mandatory mixing of bio-ethanol in transportation fuel has been implemented for dual purposes of using US surplus corn products as raw material for bio-ethanol and simultaneously safeguarding US farm economy, which prompted legislation and implementation of mandatory mixing of bio-ethanol in transportation fuel.

More specifically, Energy Policy Act of 2005 paved a way for RFS program which led to more concrete implementation plan in 2007 via Energy Independence and Security Act. The US Environmental Protection Agency (EPA) announced Regulatory Impact Assessment (RIA) in 2010, and RFS2 program was thus made available to the public, where LCA was required for the greenhouse gas evolution during the bio-ethanol production.

In many countries, government-level subsidies are being curtailed for bio-alcohols with no significant contribution to the greenhouse gas reduction. For example, cellulosic bio-ethanol is given higher Renewable Identification Number (RIN) credit in the United States for its efficient greenhouse gas reduction and non-edible nature of raw material. RIN credit ratio is 0.85:2.85 for corn-based ethanol/cellulosic bio-ethanol, which sets a higher ratio for the cellulosic ethanol.

## 8. Methanol economy

Methanol economy had been touted as a possible replacement for fossil fuel society. Now, hydrogen economy is starting to replace the momentum of methanol economy. Methanol has quite versatile usages in many sectors of modern industries for energy source and chemical raw material, which is a very good point when selling the product. Compared to the recent unmatched supply-demand issue in bio-ethanol, the point that there are many selling market can be a major advantage.

Related technologies to methanol are mostly mature such that there are only economic uncertainties, not major technical difficulties. Its related utility can expand as an energy media for society if cost is appropriate with eventual goal of replacing fossil fuels with methanol.

Methanol is produced from various raw materials including biomass or wastes which has not been fully utilized till now. Methanol-based energy can be quite useful especially for developing countries to cope with global climate change issue and related environmental issues while simultaneously securing some portion of national energy security. But, the issue of slipping into underground water stream when it is not properly regulated might be an issue that is to be solved. Underground water contamination shall be much smaller than the case by petroleum-based liquid fuels, but it needs to be comparable eventually to hydrogen and clean gas energy sources.

## 9. Relationship with hydrogen society

Hydrogen economy that is being a focal point in several developed countries can be a chance as well as danger to alcohol fuels. It is a chance because hydrogen can be manufactured with easily distributable alcohols but can be a danger when all liquid fuel-based infrastructure might be changed to the fully gas-based or hydrogen system in the long run.

Due to the concerns on climate change that requires $CO_2$ reduction and the concerns on environmental pollutants like fine particulate and NOx, hydrogen has been hoped eventually to replace all other energy mainstream options. During the last few years, hydrogen economy has reborn as a cure for $CO_2$ and environmental issues like an ultra-fine particles and PM2.5. But due to its high cost in hydrogen production as well as in application tools such as fuel cell and still-unstable infrastructure, hydrogen era might come after few decades of development and trial and errors. In contrast, alcohol fuels have been viewed as a cheap and reliable option in replacing fossil fuels. Especially, the possibility of utilizing abundant biomass prompts to try many ways in technology development and commercialization.

Hydrogen is the most abundantly available element in the universe with immense possibility as essential energy source sometime in the future. At present, however, technologically and economically viable means of its utilization as an affordable energy source are not ready and many countries opt to pursue the hydrogen economy path as a mean for dealing with climate change and pollution problems in their major cities.

Hydrogen economy involves the generation of renewable electricity from photovoltaic cell or wind turbine, and the so-called water-to-gas (PtG or P2G) which involves water electrolysis using the excess electricity to produce hydrogen. Green hydrogen energy generation and utilization is the ultimate goal in hydrogen economy in which society of no $CO_2$ evolution and no fossil fuels will eventually be accomplished. On the other hand, methanol society focuses on the production of $CO_2$-free energy source from renewable biomass or sea algae which grow by photosynthesis in nature. Green hydrogen energy will be further refined to maturity, at least by the 2030s, in such countries that can afford to bear the related high costs.

More specifically, introduction of fuel cell vehicle using hydrogen will initiate and further expand in those countries which suffer from persistent air pollution (China, Korea, Japan, large metropolis areas of the EU and United States). In contrast, alcohol-based energy source such as ethanol and methanol is most suitably applicable in tropical or semitropical countries where biomass resources are abundantly available, while domestic energy sources are not plentiful.

For realization of such alcohol-based energy generation from raw material of (very low) calorific value per unit volume, the current high-cost situation related to the pretreatment and production processes should be solved.

## 10. Ways for wider utilization

Changing the basic liquid fuel infrastructure that can accommodate alcohol fuels in a global scale will be slow like maneuvering a massive ship and very competitive even with right environmental slogans such as renewable, clean, and sustainable for the society. It is a well-known hidden fact that major local oil companies as well as auto manufacturers do not want to change their market unless certain compulsory regulation applies or proper incentives are given.

A report in July 2019 [28] on the US ethanol industry nearing breaking point succinctly shows the problem related to enlarged supply and dwindling demand. Report says that US ethanol production in early June 2019 reached almost 1.1 million barrel/day, the highest seasonally on record, but the economic margins to produce ethanol are at the lowest seasonally since 2015. Infrastructure for E85 gasoline as well as government policy like US Small Refinery Exemptions (SREs) plays key roles in demand side of alcohol fuels. This situation illustrates the weak point of alcohol fuel industry. Technical endeavor only cannot make a way for wider utilization. Policy and infrastructure should follow in parallel.

Food vs. fuel controversy is the main topic in utilization of alcohol fuels, which pushed the feedstock from corn to non-food lignocellulosic biomass. Technical breakthroughs in solving the difficulties in non-uniform/hard-to-break lignocellulosic biomass and in lowering the process cost are key factors, although it would not be an easy task, considering the already established relatively cheaper bio-ethanol industry from corn.

There are clear directions, especially in developing countries in Africa and Southeast Asian countries, where environmentally benign liquid fuel supply is in great need and the centralized energy supply infrastructure might be too costly. When alcohol fuels can be supplied in enough quantity with reasonable cost, securing energy security and installing the distributed energy infrastructure can be a socially acceptable justification.

### 10.1 Securing energy security

When a large volatility exists in oil and gas prices, a niche market of alternative fuels like alcohols can act a role. In the time of large availability of shale gas and shale oil in addition to a remarkably fast-advancing market share by renewable electricity, the probability in global energy price jump might be low. When the energy market situation goes down to local scale, however, there are many volatility in liquid fuel supply chain.

Countries with scant energy resources are expected to be more actively searching for a way to utilize pre-existing affordable energy source and raw materials for chemical industries instead of solely relying on imported natural gas and petroleum oil. It is necessary to diversify energy sources to satisfy domestic demand even for a small proportion at the start. Alcohol fuel could take some of such small proportion.

Since most countries prefer to use gas as a basic energy source, resulting in more demand for clean and easy-to-use gas resources, even Southeast countries which are currently gas-exporting countries are going to be net importer from the 2030s, as shown in **Figure 13** [29]. Energy diversification through alcohol fuels must be a practical option to ease the burden in transportation and energy utilities in these countries.

Because the demand for natural gas is large and the accommodating space is limited in urban areas, the centralized gas supply by pipeline appears to be essential. On the other hand, local villages and smaller township can satisfy their energy needs in a distributive way by alcohol fuels produced from locally available biomass

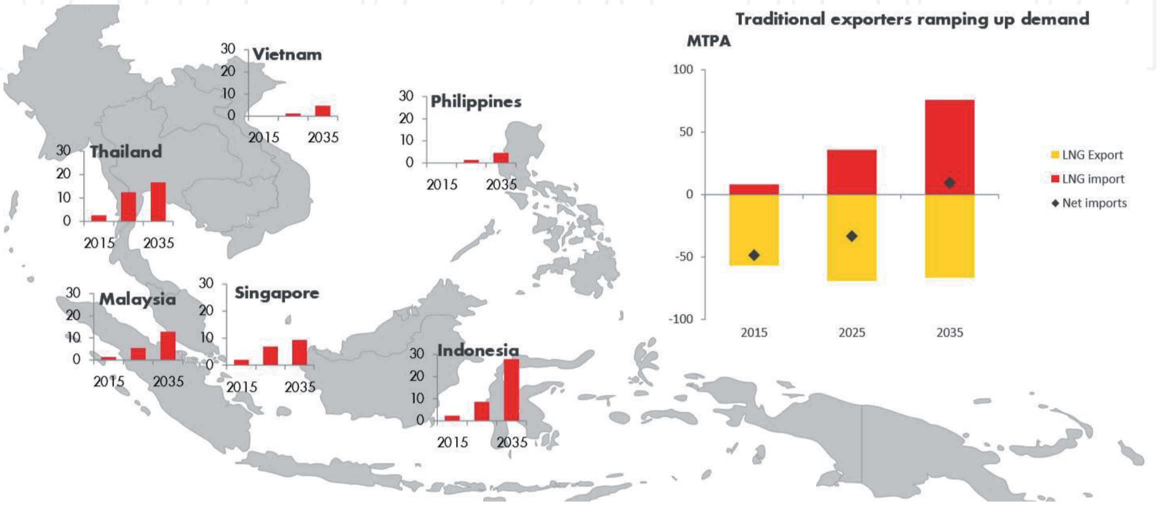


**Figure 13.**
*LNG trend change into net importer by 2035 of Southeast Asian countries [29].*

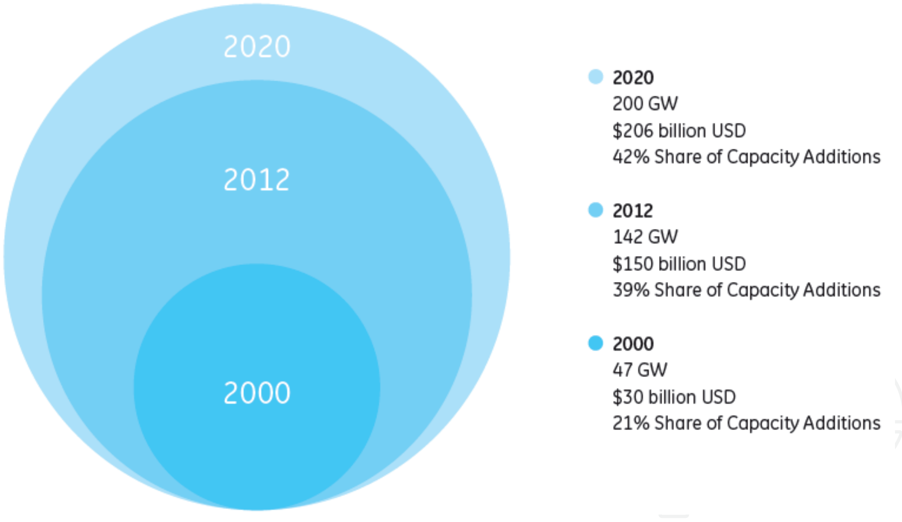


**Figure 14.**
*Worldwide distributed energy market prospect of less than 50 MW scale [30].*

and wastes. At present level, relevant technologies are not fully ripe, which necessitates international cooperation for comprehensive and interdisciplinary R&D.

### 10.2 Distributed energy applications

Future trend of energy utilization is in the type of distributed application. There are many limitations for making the system that will be competitive to the centralized big-scale system that has a huge advantage in the economics of scale.

Nevertheless, the preference for the distributed energy system that is more suitable in effectively responding to the local energy demand is on the increase worldwide recently over centralized energy distribution systems. Distributed energy system market is expected to steadily expand, and this trend is most significant in the field of less than 50 MW output, where the gas turbine is taking large proportion of market share. Alcohol fuel is also expected to play a significantly important role in the distributed energy system market (**Figure 14**).

Locally produced biomass, wastes, and agricultural by-products are converted to alcohol fuels for energy sources, and they are locally distributable and consumed. Such system is cost-competitive by minimizing the transportation distance and is important as the basic infrastructure in securing the clean energy source as well as in proceeding to the sustainable society. However, the distributed energy application system costs more than the centralized energy distribution system, in general. It can be accomplished only by meeting the pre-conditions that cost should be down significantly and proper commercialization with reliable technologies should be available for greenhouse gas reduction and for alleviation of environmental pollution.

## 11. Future direction

There emerged several candidates that compete with alcohol fuels in the twenty-first century liquid fuel field. Green hydrogen and green electricity are the most prominent players. Whether alcohol fuels can compete with these two players will depend on the future progress in dealing with key required target: $CO_2$ reduction, environmental cleanness, convenience in existing infrastructure, and price competitiveness. Moreover, energy-related focal points nowadays are sustainability, suitability for carbon-free (green energy) status, and alleviation of polluting materials such as fine dust, which are primarily emerging and ecologically important topics.

Replacement of fossil fuels with alternative clean fuel will eventually lead to green energy-based sustainable society. However, currently available technology is not up to the level of commercially viable standard for social acceptance in terms of $CO_2$ evolution and fine dust, etc., which must be comprehensively overcome.

Currently available elementary and applied technology can be utilized to synthesize liquid fuel in various forms. Although synthesis of liquid fuel is more costly than direct mining of petroleum, the application of currently available technology to alcohol fuel synthesis should be tried to make ways that can be economically feasible and lucrative when commercialized. In a sense, it is rather a problem-solving for cost-effective technology rather than the technology itself. Mass production of lignocellulosic ethanol necessitates economically competitive technology rather than the barely profitable or only technically feasible technologies.

Actually, bio-alcohol such as bio-ethanol is an industry of low unit cost. Without installing a proper scale of plant size, cost competitiveness with other liquid fuels must be quite low [13]. Actual plant construction cost remains high because of the inherent limitation of using low-energy density raw feedstock and of complex nature involved in converting into alcohol fuels. Among these, pretreatment/detoxification and hydrolysate conditioning processes are especially costly. Such auxiliary processes have to be developed in such a way that overall process cost can be dramatically reduced through the introduction of more energy-efficient and process simplification [13].

Another important aspect is that soils and climates in much of Africa have similar characteristics to those in Brazil [31]. Africa and South America have a great potential in increasing bio-energy products including alcohol fuels.

In short, alcohol fuels should work as an energy source that can minimize the environmental impact as lower than natural gas at all applications while opening more applicable places as well as manufacturing a cheaper liquid fuel that can be used in big scales also in developing countries where plentiful but low-grade raw materials exist in plenty.

## 12. Conclusions

Alcohol fuel is one of the most important source of energy in view of its renewable nature and the abundance of feedstock on earth. Even when many bright prospects of alcohol fuels shed light on possible options for the environmental conscious society, still cost dictates and it will be that way. Carbon taxation might help, but the market might lead to a totally different direction such as hydrogen or green electricity from renewable energy, instead of choosing alcohol fuels. Abundant shale natural gas might play a replacing act of cheap oil that had prevented most of other energy source developments from the 1950s till the 1970s. All these situation point that the future of alcohol fuels depends upon the technological advances in cost and convenience in use.

As discussed in this chapter, the direction of future energy is simple and clear. It is the low-carbon economy using sustainable energy resources but with affordable cost. Alcohol fuels can act as connecting threads between current conventional oil/gas society and the future hydrogen society in attaining this far-reaching goal.

Current status regarding alcohol fuels can be summarized as stagnant in scale and also in utilizing market. Since bio-ethanol dominates the alcohol fuel market, the system has an inherently sensitive structure to changes in supply-demand and government's policies. More wide application ranges of alcohol fuels should be sought in areas such as fuel cells, marine ships, and jet fuels. Alcohol fuels must remain as an essential component for the realization of sustainable low-carbon society, and continuous research on key bottlenecks should be pursued systematically.





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