# Chapter 2
# Evolving Energy Scenario: Role and Scope for Alternative Fuels in Transport Sector

**Akhilendra P. Singh, Atul Dhar and Avinash Kumar Agarwal**

**Abstract** Due to rapidly increasing energy consumption rate, access to clean, affordable and sustainable energy has become one of the important factors for economic development of any country. Depletion of petroleum reserves and associated issues related to their utilization in internal combustion (IC) engines motivated researchers to explore such alternative energy resources. In this quest, researchers have developed various solar-based and water-based energy generation methodologies; however, these techniques are not mature enough to fulfil the current energy requirements of transport sector. Therefore, appropriate alternatives to liquid fossil fuels (mineral diesel and gasoline) have been explored, in which gaseous fuels (compressed natural gas (CNG), liquefied petroleum gas (LPG), dimethyl ether (DME), Hydrogen, HCNG, etc.), biofuels [alcohols, biodiesel, straight vegetable oil (SVO)], synthetic fuels, etc., are the important ones. Utilization of microbes to produce biofuels has also gained significant attention of researchers. This chapter provides a snapshot of the current energy landscape, available options and discusses the path forward, which can be used for the development of sustainable and secure energy options for our nation.

**Keywords** Alternative fuels · Biofuels · Hydrogen · DME

## 2.1 Introduction

Energy is a basic requirement for the economic development of any country. The geographical distribution of petroleum resources is changing as reserves are being discovered and accessed using improved exploration technologies; however, this

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distribution of oil supply generally does not coincide with where the demand is located. This results in high fuel costs, which mainly depend on crude oil price. Growing energy consumption has resulted in India becoming increasingly dependent on fossil fuels such as coal, oil and gas. Fossil fuels supply more than 80% energy for global consumption and ~95% energy for the transport sector (Fig. 2.1). Figure 2.1 shows that ~95% of transport energy comes from petroleum, while the rest of transport energy is supplied by natural gas, biofuels and electricity. The light-duty vehicles (LDVs), including light-duty trucks, light commercial vehicles and mini-buses, account for about 52% fuel requirements, while trucks, including medium and heavy-duty, account for 17% fuel requirement. Remaining share of road transport energy is consumed by buses (4%) and two/three-wheelers (3%) (World Economic Forum 2011).

In 2009, the global population was 7 billion, which is estimated to grow to 9 billion by 2050 and ~10 billion by 2100 (Lee 2011). Rapidly growing population is another major factor affecting the energy sector because increasing population

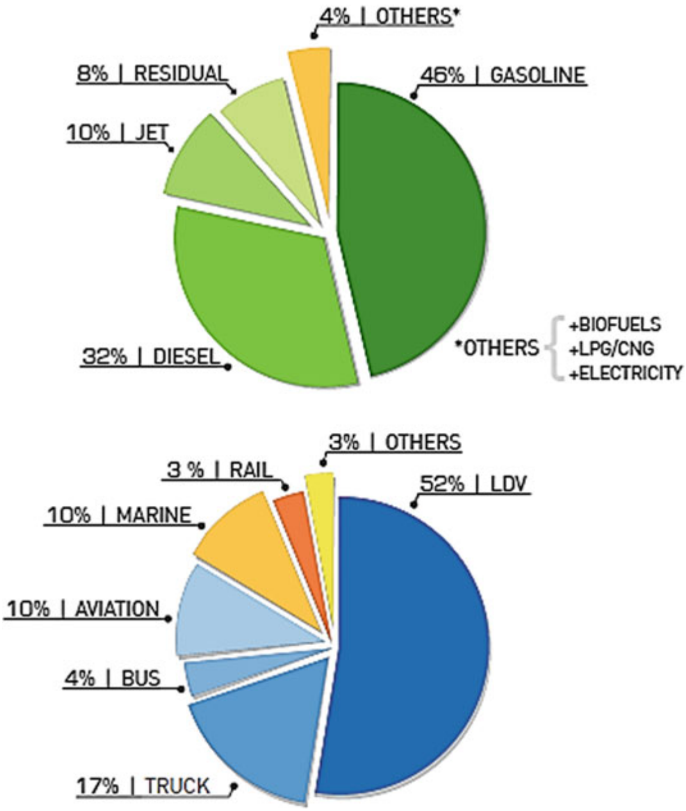


Fig. 2.1 Current global transport energy sources and consumption trends (2011) (World Economic Forum et al. 2011)

requires more energy, which puts extra burden on the global economic development. The International Energy Agency (IEA) has projected that global energy demand will increase from ~12 billion tonne oil equivalents (TOE) in 2009 to ~17 or 18 billion TOE by 2035 under the 'current policies' or 'new policies' scenarios, respectively (International Energy Agency 2017). This data shows that the world is already in an alarming situation, and these figures need to be brought down by a great extent to improve the survival of human species. Figure 2.2 shows the importance of fossil fuel in transport and energy generation sector. The growth in use of fossil fuels is increasingly driven by the transport sector, where fossil fuels make up ~95% of transport energy. Electricity generation is also significantly controlled by fossil fuels because 48% electricity is generated by coal, 19% by natural gas, 21% by nuclear power, 10% by renewables and 1% by oil.

While global fossil fuel reserves are diminishing, worldwide energy demand is constantly increasing due to evolution of energy intensive life-styles. Experts estimate that the global demand for energy could rise by >50% between 2009 and 2030 and the oil production will reach a peak around 2020–30. Burning fossil fuels generates $CO_2$, a greenhouse gas (GHG), leading to global warming. It is therefore necessary to find cleaner fuels, which do not originate from fossil resources. Vehicular pollution cannot be avoided because the pollutants are emitted at the ground level, close to human breathing level. Severity of vehicular pollution is reflected in increased human mortality and morbidity. Vehicular pollution affects human health adversely due to presence of carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NOx), suspended particulate matter (SPM) and aldehydes, amongst others in the engine exhaust. Apart from these harmful pollutants, $CO_2$ leads to various long-term global problems including greenhouse effect/global warming. Almost all countries are working on the methods for $CO_2$ emission reduction from engine tailpipe to combat this menace. Different

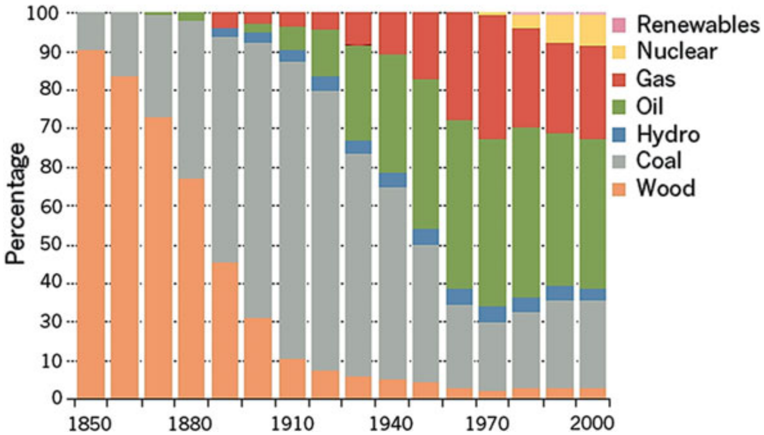


**Fig. 2.2** History of relative mix of main energy resource used in the USA (Energy Information Administration. Annual Energy Review 2010)

**Table 2.1** Alternative fuels landscape

| SN | Fuel | Description | Remarks |
|---|---|---|---|
| 1 | CNG | Compressed natural gas contains methane, which is an environment-friendly fuel, which lowers CO and HC emissions | Used for three-wheelers, passenger cars, LCVs and HCVs |
| 2 | LPG | Liquefied petroleum gas contains propane and butane, which lowers CO and HC emissions | Used for three-wheelers and passenger cars |
| 3 | HCNG | Blend of hydrogen and natural gas, used as a trial fuel and not commercially introduced yet | Proposed for HCVs |
| 4 | LNG | Liquefied natural gas improves carrying capacity of vehicle and is not yet commercially introduced yet | Proposed for HCVs |
| 5 | Biogas | Biogas contains methane, an environment-friendly fuel, lowers CO and HC emissions | Proposed for LCV and HCVs |
| 6 | Alcohols | Alcohols are blended with gasoline at a 5% blend, which is proposed to be increased to 10% | Used for some passenger cars and SUVs |
| 7 | Biodiesel | Esterified vegetable oils, which can be blended with diesel | Used for SUVs and HCVs |
| 8 | Synthetic fuels | Artificial fuels derived from natural fuels using Fischer–Tropsch process | Proposed for passenger cars |
| 9 | Hydrogen | Freedom fuel, which is currently under trial | Proposed for Passenger cars and HCVs |

air pollutants from vehicles have adverse effects at all levels—localized (e.g. smoke affects visibility, ambient air quality), regional (such as smog, acidification) and global (i.e. global warming).

To resolve these issues, researchers and oil companies have been directed towards promoting the use of alternative fuels, which are affordable, sustainable and environment-friendly and can fulfil the requirements of transport sector. Table 2.1 shows the landscape for potential alternative fuels.

## 2.2 Available Alternative Fuels

In order to meet increasingly stringent emission norms, researchers are exploring use of alternative fuels, which can be adopted in current generation engines with minimal hardware modifications. It is expected that the emissions from such alternate fuels should be lower than the emissions from conventional fuels. In this quest, several alternative fuels have been researched and developed. Researchers are primarily looking at low carbon fuels in order to reduce greenhouse gas emissions. Several alternative fuels such as biodiesel, CNG, ethanol, hydrogen, vegetable oils, LPG, hydrogen-CNG (HCNG) blends have been investigated for their engine performance in order to assess their technical feasibility.

### *2.2.1 Gaseous Alternative Fuels*

#### 2.2.1.1 Natural Gas

Natural gas is a mixture of ethane, propane, butane, carbon dioxide, nitrogen, etc., with 80–98% methane, which is the main constituent, depending upon source of production (Korakianitis et al. 2011; Ramadhas 2011; Lee et al. 2007). Fossil natural gas is found either together with other fossil fuels (such as crude oil in oil fields, or coal in coal beds) or on its own. CNG has been used in public transport buses, heavy-duty commercial vehicles and light-duty personal vehicles. In SI engines, it offers several advantages such as possibility of increasing engine efficiency (with associated reduction in $CO_2$ emissions) by increasing engine's compression ratio due to higher octane rating of natural gas compared to gasoline, reduction in quantity and toxicity of HC emissions, reduction in CO emissions, etc. It can be also utilized in retrofitted CI engines, which include modifications such as installing an ignition source, reduction of compression ratio and retrofitting a fuel storage and delivery system, which results in reduction in local pollution. Utilization of natural gas in SI engines results in 10–15% reduction in power output compared to gasoline-fuelled engines, which may be compensated by direct injection of fuel with expected availability of special injectors in near future (Korakianitis et al. 2011). Currently, for vehicular use, natural gas is stored in cylinders at 200 bar pressures, however, range of natural gas-fuelled vehicles still remains significantly lower than gasoline and diesel-fuelled vehicles due to its lower energy storage density (Korakianitis et al. 2011; Ramadhas 2011).

Share of natural gas amongst global transport fuels is predicted to remain in the range of 3–3.7% up to 2035 according to EIA world energy outlook (2011). Though natural gas is a non-renewable source, its main constituent methane can be produced from biomass as well, which is a renewable resource (Porpatham et al. 2008). Waste biomass can be utilized as transport fuel by producing natural gas, biomass-to-liquid (BTL) and ether from it. The process of collecting, purifying and using methane obtained from biomass decomposition is relatively simpler compared to Fischer–Tropsch process used in gas-to-liquid (GTL) and BTL processes (Korakianitis et al. 2011). However, at current stage of technological development, well-to-wheel energy consumption (3.5 MJ/km) of methane (D'Agosto and Ribeiro 2009) obtained from biomass is higher than fossil natural gas, gasoline and diesel (2 MJ/km) (Dimopoulos et al. 2008). Future developments in natural gas-fuelled engine technology and gas purification technology may ensure more efficient utilization of renewable methane.

#### 2.2.1.2 Liquefied Petroleum Gas

Liquefied petroleum gas (LPG), another gaseous, fossil origin, alternative fuel, is mainly a mixture of butane and propane. It is derived from lighter hydrocarbon fractions produced during refining of crude petroleum as well as from the heavier components of natural gas, which are removed before the gas is distributed (MacLean and Lave 2003). Before further processing and transportation of crude oil or natural gas, heavier gases, which constitute LPG, are separated. LPG is also produced during atmospheric distillation, reforming and cracking of crude oil. Separation of propane and butane like gases from crude oil is necessary for its stabilization before its distribution through pipeline or tanker (Ramadhas 2011). Its engine utilization is similar to natural gas with additional advantage of higher storage energy density since it can be easily liquefied and stored as a liquid fuel at moderate pressure of 10–12 bars. However, cold-starting and cold-start emission characteristics of LPG are inferior to natural gas (Ramadhas 2011; MacLean and Lave 2003), which need to be tackled technologically.

#### 2.2.1.3 Hydrogen

In the quest for operating the engine with improved efficiency and lower emissions, hydrogen has emerged as a prominent alternate fuel candidate. For running the engine using hydrogen, several modifications are required to be done in the existing engines. Hydrogen is an energy carrier and not an energy source because free hydrogen is not available in nature and some form of primary energy is required to be spent for hydrogen production (MacLean and Lave 2003; Verhelst and Wallner 2009). Its usefulness as an energy carrier is limited by its low energy content on a volume basis, limiting its on-board storage (MacLean and Lave 2003). Primary advantage of hydrogen over other fuels is its clean exhaust. Its oxidation does not produce carbon dioxide and other carbonaceous harmful species. Hydrogen is used as transport fuel via two routes: hydrogen fuel-cell ($H_2$ FC) vehicles and hydrogen IC engine ($H_2$ ICE) vehicles. Addition of hybrid electric vehicle (HEV) technology improves the fuel economy of both the powertrains. Currently, efficiency and cost of $H_2$ FC powertrain are higher than $H_2$ ICE powertrain (Verhelst and Wallner 2009). Generally, hydrogen can be produced by electrolysis or thermal decomposition of water, steam reforming of natural gas and other hydrocarbons, pyrolysis of hydrocarbons, plasma refining process, etc. (Ramadhas 2011; Lee et al. 2007). Steam reforming of natural gas converts it into synthesis gas, from which $CO_2$ and CO are removed (Ramadhas 2011). Method of hydrogen production, which requires production of an interim energy carrier like electricity prior to production of hydrogen has significant efficiency disadvantages (MacLean and Lave 2003). Abbott proposed possibility of using solar hydrogen produced by solar thermal collectors through $H_2$ ICE route as a viable and promising solution for future transport solution for large-scale application (Abbott 2009).

#### 2.2.1.4 HCNG

CNG, being produced from fossil as well as natural resources, is a good alternative to liquid fossil fuels. It is relatively abundant and easily available compared to hydrogen. However, it has lower flame speed, shorter flammability range and other limitations, which make it a sub-optimum fuel for IC engines. Hydrogen, which can be produced from renewable resources as well, is a possible solution to some of these issues. However, hydrogen has its own limitations in terms of low storage energy density. It occupies very large volume as a gas, and storing it in liquid form is extremely energy intensive. There is a sharp contrast in vital properties of both these fuels; therefore, many researchers proposed blending hydrogen and CNG for IC engine applications. HCNG mixtures result in relatively lower emissions since they have higher H/C ratio. Therefore, they have the potential to replace conventional liquid fossil fuels in an environment-friendly manner. Nagalingam et al. (1983) studied the performance of an AVL research engine using CNG, hydrogen and hydrogen/CNG blends as early as in 1983. Engine Research Lab (ERL) at IIT Kanpur has conducted significant research on HCNG including development of HCNG engines and development of laser ignited HCNG engine, which are cited in this chapter to help understand the characteristics of HCNG as an alternate IC engine fuel (Hora et al. 2016; Hora and Agarwal 2015).

### 2.2.2 *Biofuels*

Biofuels have attracted growing attention of policy makers, industry and researchers. Biofuels are combustible materials, which can be derived directly or indirectly from biomass, produced from plants, animals and micro-organisms from the renewable organic wastes. Biofuels may be solid, liquid or gaseous and originate from all kinds of biomass and derived products used for energetic purposes. Biofuel production process and typical classification of fuels are shown in Fig. 2.3.

#### 2.2.2.1 Primary Alcohols

Methanol, ethanol and butanol and their blends with gasoline are used as alternative transport fuels in SI engines (Agarwal 2007; Nigam and Singh 2011; Balki et al. 2012). Methanol is the shortest carbon chain primary alcohol and burns cleanly due to its simple chemical structure and high oxygen content ($\sim$50%). Ethanol is similar to methanol, however, it is relatively cleaner, less toxic and less corrosive compared to methanol (Agarwal 2007). Compared to other primary alcohols, butanol is far less corrosive and can be distributed through existing pipeline networks and filling stations (Nigam and Singh 2011). Use of lower gasoline-alcohol blends in SI engines results in reduction of CO, HC and NOx emissions while producing almost similar engine torque output (Agarwal 2007; Balki et al. 2012).

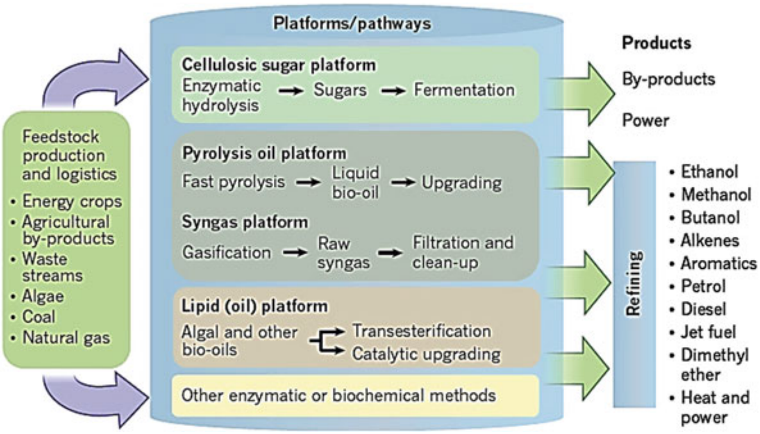


**Fig. 2.3** Methods of producing alternative fuels from various biomass feedstocks to products (US Department of Energy 2011)

However, aldehyde emissions increase with alcohol-fuelled operation of IC engines (Agarwal 2007). For using higher blends of alcohols in SI engines, some engine modifications are essential to cater to their higher octane number, lower volatility, lower calorific value and different chemical reactivity vis-à-vis that of gasoline (Agarwal 2007; Kremer et al. 1996). Alcohol blends can also be used in CI engines as supplementary fuels (Ramadhas 2011; Agarwal 2007). For use of higher concentration ethanol blends (>20% v/v), fuel additives are required for stabilizing the mixture and attaining desired cetane number (Ramadhas 2011). Higher percentage of ethanol in diesel requires a double injection or fumigation system, which is helpful in emission and noise reduction but increases control complexity (Ramadhas 2011). Alcohols can also be used in blended form with straight vegetable oils, biodiesel and mineral diesel (Yilmaz and Sanchez 2012; Kumar et al. 2003). Alcohol–biodiesel–diesel blends result in reduction in NOx and particulate emissions in CI engines (Kumar et al. 2003; Shi et al. 2006; Zhu et al. 2010). Transesterification process for biodiesel production utilizes methanol/ethanol and vegetable oils as process inputs. This route of utilizing alcohols as a diesel engine fuel is definitely a superior route because aldehyde emissions and corrosion of engine parts by alcohols are drastically reduced this way (Nigam and Singh 2011).

#### 2.2.2.2 Straight Vegetable Oils and Derivatives

Plant-derived oils, waste cooking oils or any other waste/residue triglycerides can be converted into diesel-like fuels through several routes. Vegetable oil-based fuels are biodegradable, non-toxic, and they have potential to significantly reduce environmental pollution. Vegetable oils have 90% heat content of mineral diesel, and they have a favourable output/input ratio of about 2–4: 1 for unirrigated crop production. In India, the current prices of vegetable oils are almost equivalent to that of petroleum-derived fuel prices. From amongst large number of vegetable oils available in the country, if any specific oil needs to be adopted as a continuing energy crop, then it is essential that this oilseed variety should have higher productivity and oil content. However, these vegetable oils have several issues such as low volatility and ability to polymerize (due to unsaturation). This leads to undesirable issues such as carbon deposits in the engine combustion chamber, injector coking and piston ring sticking (Agarwal 2007; Galle et al. 2012). To eliminate these issues, straight vegetable oils are converted into biodiesel, which has very similar properties as that of mineral diesel, and is currently one of the most accepted routes (Gerhard 2010). Biodiesel as an alternative transport fuel for CI engines is discussed in greater detail in the next section of this chapter. Another fuel with properties and composition similar to mineral diesel can also be produced by hydro-de-oxygenation of triglycerides. It is termed as hydrotreated vegetable oil (HVO) or renewable diesel (Gerhard 2010; International Energy Agency 2011; Huber and Corma 2007) or green diesel. In hydro-de-oxygenation process, a feedstock containing double bonds and oxygen moieties can be converted into hydrocarbons by removal of oxygen and saturation of double bonds (Gerhard 2010). Cold flow properties of renewable diesel are superior to mineral diesel, but currently, technology for its commercial production is in development stage (Gerhard 2010; International Energy Agency 2011).

#### 2.2.2.3 Biodiesel

Vegetable oils in their raw form cannot be used in CI engines due to their inferior fuel properties; therefore, they have to be chemically modified to produce biodiesel, which has improved physical and chemical properties for use as a fuel. Biodiesel is a chemically modified alternative fuel for diesel engines, derived from vegetable oil fatty acids and animal fats. This is done using transesterification process, in which the reaction of triglycerides present in the vegetable oils is done with primary alcohols in presence of a catalyst, which produces primary esters (biodiesel) and glycerol (Agarwal 2007).

Base-catalyzed transesterification is the most common process used for production of biodiesel because it involves low reaction temperatures and pressures, low-cost material of construction and high process yield for good-quality feedstock (of low free fatty acid (FFA) and moisture content). The resulting biodiesel is quite similar to conventional diesel in its main characteristics. The process of transesterification brings about drastic changes in density and viscosity of vegetable oils. The biodiesel produced by this process is completely miscible with mineral diesel in any proportion to create a stable blend. Viscosity of biodiesel comes very close to that of mineral diesel; hence, problems related to fuel handling system are reduced. Transesterification process lowers the flash point of biodiesel and increases the cetane number, which is helpful in reducing the ignition delay. Therefore, lower concentrations of biodiesel can act as cetane improver for biodiesel blends. The heating value of biodiesel is close to mineral diesel. These properties make biodiesel suitable for CI engines without any major hardware modifications.

### *2.2.3 Unconventional Fossil Oils*

Fossil fuel resources, whose extraction and conversion into liquid fuels is comparatively difficult and expensive, are referred as unconventional oils. Extra-heavy oil, natural bitumen (oil sands, tar sands) and oil shale are three important sources of unconventional oils (Mohr and Evans 2010). Extra-heavy oils are much more difficult to recover in comparison to conventional petroleum. Constituents of heavy oil have significantly higher viscosity than conventional petroleum, and primary recovery of heavy oils usually requires thermal stimulation of the reservoir. Natural bitumen also known as 'tar sand' and 'oil sand' is impregnated with dense, viscous organic material called bitumen (Lee et al. 2007; World Energy Council 2010). Oil shales are fine-grained sedimentary rocks, from which significant amount of shale oil and combustible gas can be extracted by destructive distillation (Mohr and Evans 2010; World Energy Council 2010). The presence of large amount of organic matter, known as 'kerogen', is the major source of oil and gas in oil shales. According to EIA, largest fractions of future unconventional liquid fuel production include 239 MTOE/year of Canadian oil sands, 69.7 MTOE/year of Venezuelan extra-heavy oils and 194.2 MTOE/year of biofuels (109.6 and 84.7 MTOE/year of the USA and Brazilian biofuels, respectively) (U.S. Energy Information Administration 2011). Unconventional fossil oils are predicted to account for roughly 7% of global liquid fuel supply by 2035 (U.S. Energy Information Administration 2011).

### *2.2.4 Other Alternative Fuels*

#### 2.2.4.1 Fischer–Tropsch Liquids

Fischer–Tropsch (F–T) process is a process that produces variety of hydrocarbon fuels. The primary product is a diesel-like fuel from syngas ($H_2$/CO), which can be produced by auto-thermal reforming of natural gas, biomass or coal (MacLean and Lave 2003; Nigam and Singh 2011; Gill et al. 2011). Depending on the starting material, process could be known as coal-to-liquid (CTL), gas-to-liquid (GTL) and biomass-to-liquid (BTL) conversion process. The F–T liquid fuel has no sulphur, almost no aromatics and high cetane number. These properties make this an attractive alternative fuel for CI engines (MacLean and Lave 2003). The feedstock for BTL is renewable and can be produced with biomass residues from food crops with minimal interference to the food economy and much less strain on land, air and water resources compared to alcohols or oilseed-based fuels. However, the conversion technologies such as hydrolysis and gasification are still under development (Gill et al. 2011).

#### 2.2.4.2 Dimethyl Ether

Dimethyl ether (DME: $CH_3$-O-$CH_3$) exists in the form of a colourless gas at room temperature with slight odour. It is necessary to keep it in closed containers for normal use and distribution (Ramadhas 2011). Vapour pressure of DME lies in between propane and butane (Ramadhas 2011). DME is considered clean-burning alternative fuel for CI engines and is helpful in reducing local air pollution. It may be easily auto-ignited due to its high cetane number and results in practically soot-free combustion due to easy vaporization and absence of carbon-to-carbon bonds (Park and Lee 2013; Semelsberger et al. 2006). Like hydrogen and F–T liquids, it is also not found in nature. For DME production, organic feedstocks such as biomass, coal or natural gas are converted into synthesis gas, which is a mixture of carbon monoxide, hydrogen and some other gases. Syngas is converted into methanol and finally into DME by dehydrogenation of methanol (Ramadhas 2011; Park and Lee 2013). Power output of DME-fuelled engines is lower than diesel-fuelled engines due to significant differences in properties of diesel and DME such as higher compressibility and lower heating value of DME than mineral diesel. Lower fuel lubricity and viscosity of DME cause durability issues in fuel injection system, which needs to be resolved in order to adopt to this wonderful fuel at a large scale (Park and Lee 2013).

## 2.3 Conclusions

Above discussions clearly show that the twin crises arising out of fuel starvation and environmental degradation can be resolved by adopting sustainable and environment-friendly alternative fuels. For the developing countries like India, biofuels can provide a feasible solution to tackle these crises. These biofuels may be alcohols, vegetable oils, biomass, biogas, etc. Some of these biofuels can be used directly in the IC engines, while others require to be formulated to bring the relevant properties close to conventional fuels. There are number of serious reasons for using biofuels as alternative fuels, e.g. expected growth of prices of fossil liquid fuels in the near future, gradual depletion of crude oil resources in the next 80–100 years, etc. Devastated land excluded from food production may be used for biofuel production globally. Compared to conventional fuels, the harmful emissions in exhaust gas using biofuels are significantly lower. In India, most of the agricultural and transport energy requirements are fulfilled by mineral diesel as of now; therefore, it is essential that alternatives to mineral diesel should be developed on a priority basis. Apart from renewable energy technologies, a number of steps should be taken for promoting conservation of fossil fuels. These include improving energy efficiency of refineries, increasing fuel efficiency in the transport sector, greater utilization of CNG as a fuel in transport sector, upgradation of lubricants and promotion of fuel-efficient equipment and practices in industrial sector.

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