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Review Article

Biofuels and the Hybrid Fuel Sector

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To enable India to cope with the predictable and challenging situation of a scarcity of petroleum fuels for surface transport in the future, we examine and evaluate in this study potential alternatives that can ensure adequate energy for the transport sector with acceptable environment implications. These alternatives can be broadly categorized into three groups from the perspective of planning a smooth transition from a conventional petroleum fuel-based transport system to sustainable energy alternatives. The first group includes non-conventional fossil-based resources such as compressed natural gas (CNG), liquefied petroleum gas (LPG), methane from coal beds and gas hydrates, shale oil, shale gas, etc. Use of these resources could provide energy security but cannot guarantee environmental benefits. The second group includes first generation biofuels (alcohol and biodiesel), and biomass-to-liquid (BTL) fuels. These fuels are renewable but their current production methods and base feedstock do not appear promising enough to provide for a large-scale supply of fuel in a sustainable manner. The third group includes second generation biofuels and hydrogen. The feasibility of large-scale hydrogen production from renewable resources holds promise for scalable implementation and sustainability in the future but this would require huge technological challenges to be overcome. This study describes the potential of this proposed fuel resource scenario for transport fuels and discusses the technological challenges that would have to be addressed for its large-scale implementation.

Keywords: Biofuels; Hybrid Fuels; Biodiesel; Alcohols; Fischer-Tropsch Liquids; CNG; DME; GTL; BTL; CTL

Introduction

We are confronted today with the twin crises of uncertainty of energy supply resulting from fossil fuel depletion and environmental degradation due to emission of harmful pollutants from the combustion of fossil fuels. In such a scenario, renewable alternative fuels hold promise for assured sustainable development with the security of energy supply along with acceptable environmental implications. Fuels for transport sector are required to meet additional challenges such as adequate energy density and lower pollutant emissions in the exhaust which are harmful for human health. Energy requirement of the Indian transport sector stood at 47.12 MTOE (million tonnes of oil equivalent) in 2008, and is expected to cross103 MTOE by 2020 and 200 MTOE by 2035 with an average annual growth rate of 5.5% (US EIA, 2011). This poses a huge challenge for energy security and its planning. In the present situation, almost all transport fuels originate from petroleum resources. Generally, fuels used in internal combustion (IC) engines, other than mineral diesel and gasoline, are recognized as alternative fuels. These alternative fuels include natural gas (NG: CNG/LNG), liquefied petroleum gas (LPG), hydrogen, unconventional fossil oils, electricity, Fischer-Tropsch liquids, ethers, alcohols, biodiesel, etc. Some of these alternative fuels are renewable while others are produced from non-renewable resources.

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For ensuring adequate and sustainable energy supply to the transportation sector, the requirement of uninterrupted fuel supply can be fulfilled by an appropriate mix of these alternative transport fuels and conventional fuels. Chapter 2 describes the availability, utilization technology, environmental impact and the role of various alternative fuels in constituting a transport fuel mix for the future.

Natural Gas

Natural gas is a mixture of ethane, propane, butane, carbon dioxide, nitrogen, etc., with methane (80-98% v/v), being the main constituent, depending on the production source (Korakianitis *et al.*, 2011; Ramadhas, 2011). Natural gas is found either with other fossil fuels (such as crude petroleum in oil fields, or coal in coal beds) or on its own in dry gas wells. It is used as a fuel in SI engines as well as in CI engines in dual-fuel mode. In SI engines, it offers several advantages, such as (i) possibility of increasing engine efficiency (associated reduction in CO_2 emissions) by increasing engine compression ratio due to higher octane rating of natural gas in comparison to gasoline, (ii) reduction in quantity and toxicity of HC emissions, (iii) reduction in CO emissions, etc. It can be also utilized by retrofitting CI engines, which include (i) modifications such as installing an ignition source, (ii) reduction of compression ratio and (iii) fitting of fuel storage and delivery system, which would result in reducing local pollution levels. Utilization of natural gas in SI engine results in 10-15% reduction in power output compared to identical gasoline-fuelled engine, which may be compensated by direct injection of fuel with the expected availability of special injectors in the near future (Korakianitis *et al.,* 2011). Currently for vehicular use, natural gas is stored in cylinders at 200 bar pressure, however the operating range of natural gas-fuelled vehicles still remains lower than gasoline and diesel-fuelled vehicles due to its lower storage energy density (Korakianitis*et al.*, 2011; Ramadhas, 2011a; Speight, 2007). Though natural gas originates from a non-renewable resource, its main constituent methane can also be produced from biomass, which is a renewable resource available in abundance (Porpatham *et al.*, 2008). Waste biomass from agriculture can be converted to transport fuel by producing natural gas, biomass-to-liquid (BTL) or ether from it. The process of collecting, purifying and using methane obtained from biomass decomposition is relatively simpler compared to the Fischer-Tropsch (FT) process used in gas-to-liquid (GTL) conversion (Korakianitis *et al.*, 2011). However, at the current stage of technological development, well-to-wheel energy consumption (3.5 MJ/km) of methane obtained from biomass (D'Agosto and Ribeiro, 2009) 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 might ensure more efficient utilization of renewable methane from biomass. In recent years, technological advancements for utilization of shale gas, coal bed methane (CBM) and the possibility of utilization of methane obtained from gas hydrates renders natural gas an extremely important fuel for future use in the transportation sector. According to an assessment by the US Energy Information (EIA; April 2011), technically recoverable shale resources in India are 63 trillion cubic feet (TCF) compared to 1,275 TCF for China, and 1,250 TCF for US and Canada combined (US EIA, 2011; Nakao *et al.*, 2008; US EIA, 2011b). Technically recoverable resources of shale gas in India are sufficient to fulfill our natural gas demand for at least the next 33 years (US EIA, 2011b).

Liquefied Petroleum Gas

Liquefied petroleum gas (LPG) is another gaseous, fossil origin, alternative fuel, which is primarily a mixture of butane and propane. It is derived from lighter hydrocarbon fractions produced during refining of crude petroleum in a fractional distillation column, it is also recovered from the heavier components present in natural gas, which are removed before natural gas is distributed and utilized (MacLean and Lave, 2003). LPG is also produced during petroleum refining processes, such as fractional distillation, reforming and cracking. Separating propane and butane from crude oil is necessary for its stabilization before it is distributed through pipelines or tankers (Selim, 2011). LPG's engine utilization is similar to natural gas with the additional advantage of higher storage energy density because it can be easily liquefied and stored as liquid at reasonable pressures (10-14 bars). However, its cold-starting characteristics and cold-start emissions are relatively inferior compared to natural gas (MacLean and Lave, 2003; Selim, 2011). LPG is expected to last as a viable fuel option as long as fossil crude oil and natural gas are available, therefore its supply potential is rather limited and is directly linked to availability of petroleum. Technology should be developed to efficiently utilize LPG as an alternate fuel in engines, which are designed to run on other fuels. In India, it is already a very popular fuel in the transport sector for dual fuel cars.

Unconventional Fossil Sils

When petroleum which is found in an underground reservoir, is a free flowing liquid, which can be recovered by pumping, it is referred to as conventional petroleum. Other fossil fuel resources, whose extraction and conversion into liquid fuels is relatively difficult and expensive, are referred to as unconventional oil. Extra-heavy oil, natural bitumen (oil sands, tar sands) and oil shale are three important resources of unconventional oil (Mohr and Evans, 2010). Natural bitumen and extra-heavy oils are remnants of very large volumes of conventional oils that have been generated and degraded, principally by bacterial action. Chemically and texturally, bitumen and extra-heavy oils resemble the residum generated by refinery distillation of light oil (WEA, 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 reservoir. Natural bitumen also known as ‘‘tar sand’’ and ‘‘oil sand’’ is impregnated with dense, viscous organic material called bitumen (WEA, 2010; Speight, 2007b). Oil shales are fine-grained sedimentary rocks containing relatively larger amount of organic matter (known as ‘‘kerogen’’), from which, significant amount of shale oil and combustible gases can be extracted by using destructive distillation (Mohr and Evans, 2010; WEA, 2010). According to estimates of the World Energy Council (2010), the resource base of natural bitumen and extra-heavy oil is immense and there can be no constraint on the expansion of production. These resources can make an important contribution to future oil supply, if they can be extracted and transformed into usable refinery feedstock at sufficiently high rates, and at costs which are competitive in comparison to other alternative resources (WEA, 2010). According to EIA, the largest fractions of future unconventional liquid fuel production includes 239 MTOE/year of Canadian oil sands, 69.7 MTOE/year of Venezuelan extra-heavy oil and 194.2 MTOE/year of biofuels (109.6 and 84.7 MTOE/year of U.S. and Brazilian biofuels, respectively) (US EIA, 2011). Unconventional fossil oils are predicted to account for roughly 7% of the global liquid fuel supply by 2035 (US EIA, 2011).

Currently, shale oil is more expensive to produce when compared with petroleum-based crude oil because of the additional cost of mining and extraction of energy from oil shale. Owing to its higher costs, only a few deposits of oil shale are currently being exploited in China, Brazil, and Estonia. However, with the continuing decline in petroleum supplies, accompanied by increasing cost of petroleum, oil shales present an opportunity of adequate supply of fossil energy to the world in the years ahead (DGA, Government of India). The Directorate General of Hydrocarbons (DGH), under the Ministry of Petroleum and Natural Gas, Government of India has embarked upon projects for the evaluation of oil shale resource potential in India and its extraction by involving international collaborations with many experienced companies working in the area of extraction of shale oil (DGA, Government of India). Currently, extraction of shale oil deteriorates the land and produces large quantities of polluted water and toxic gases, which are environmentally hazardous. Further research is therefore required for developing technological methods that are cost-effective and environment-friendly for the extraction of shale oil.

Hydrogen

Hydrogen is an energy carrier and not an energy resource because free hydrogen is not available in nature and one or the other form of primary energy is required to be invested for its production (MacLean and Lave, 2003;Verhelst and Wallner, 2009). Its usefulness as an excellent energy carrier is also limited because of its low energy content on a volume basis, limiting the possibility of its on board storage in vehicles (MacLean and Lave, 2003). The primary advantage of hydrogen over other fuels is its clean exhaust because its oxidation does not produce carbon dioxide or other carbonaceous species. Hydrogen can be used as a 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 these powertrains. Currently, efficiency and cost of H_2 FC powertrain is higher than H_2 ICE power-train (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, 2011b). Steam reforming of natural gas converts it into synthesis gas, from which CO_2 and CO are required to be removed (Ramadhas, 2011b) to generate hydrogen. The method of producing hydrogen which requires the production of interim energy carrier-like electricity prior to production of hydrogen has significant efficiency disadvantage (MacLean and Lave, 2003). Abbott proposed the possibility of using solar hydrogen produced by solar thermal collectors through the H_2 ICE route as a viable and promising solution for future transport fuel requirement for large-scale applications (Abbott, 2009). Challenges related to production and storage of hydrogen are covered in greater detail elsewhere in this volume.

Electricity

Electric vehicles use charge stored in batteries. They do not emit any combustion-generated pollutants on the roads and their operation is quieter. However, the source of electricity generation used to charge the batteries determines the life cycle emissions of this means of transportation. Electricity can be generated without creating air pollution such as by using nuclear, hydro, solar, wind energy, etc. Electricity generation by natural gas or coal however results in significant upstream emissions (MacLean and Lave, 2003). Therefore, if non-renewable sources are used for electricity production, life-cycle emissions of electricity as a transportation fuel could be significantly higher. Therefore, there is a need to develop carbon-neutral decentralized electricity generation capability. At the current level of technological advancement, batteries have low energy density; therefore, electric vehicles have a rather limited operating range (MacLean and Lave, 2003). Electrical powertrains do not bring additional primary energy source into the application but provide a way to utilize coal and nuclear energy resources for transportation and are also helpful in controlling localized on-road pollution, thereby improving urban air-quality, which is of prime importance to congested Indian cities such as Delhi, Bombay, Calcutta, Bangalore, etc. Challenges related to further developments in efficiency and ability of energy storage of fuel cells, which are currently more efficient than battery-based electricity storage systems, are covered in greater detail elsewhere in this volume.

Biofuels

Biofuel refers to solid, liquid and gaseous fuels produced from biomass (Nigam and Singh, 2011;IEA, 2011). However, from the perspective of using these as alternative mass transport fuels, the relevant biofuels are gaseous and liquid fuels such as ethanol, methanol, biodiesel, Fischer-Tropsch liquids, hydrogen, di-methyl ether, methane, etc. primarily generated from biomass (Nigam and Singh, 2011). Depending on the pressure on natural resources for unit energy production and current status of technological developments, biofuels are categorized primarily as first, second and third generation biofuels with increasing order of technological complexity, advancement and lowering the burden on natural resources.

Bioethanol and biodiesel produced from fermentation of starch and transesterification of vegetable oils are the most widely used first generation biofuels today. Fig. 1 summarizes various biofuel options and their current technology status. Generally, biodiesel and bioethanol produced from different technologies have similar properties; hence, partial mitigation towards biofuels is undertaken depending

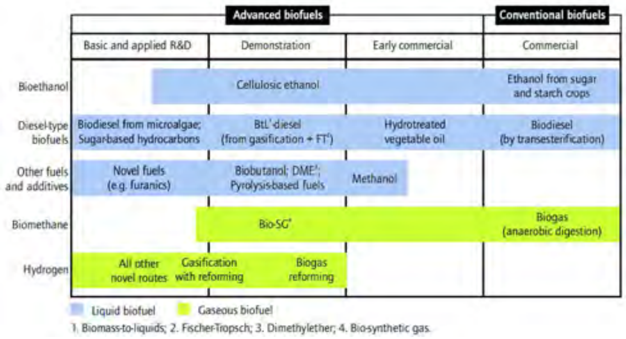

Fig. 1: Current technology status of biofuel options (IEA, 2011; Bauen *et al.*, 2009)

on the availability of feedstock for producing these fuels. The utilization of such biofuels would increase with increasing production due to advancements in fuel production technologies (Fig. 1). The current biofuel policy of the Government of India has an ambitious goal of achieving 20% blending of biofuels, both biodiesel and bioethanol by 2017, in all commercially available diesel and gasoline in the country (MNRE, Government of India). In 2010, India launched a National Ethanol Blending Programme, making it mandatory to blend 5% ethanol in gasoline across 20 states in the country. However, the supply chain and availability of bioethanol in such large quantities posed a key challenge for this programme and it could not be implemented across the board. The following sub-section describes production and engine utilization technologies of various liquid biofuels.

Dimethyl Ether

Di-methyl 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 (Spencer, 2011). Vapour pressure of DME lies in between that of propane and butane (Spencer, 2011). DME is considered as an extremely clean burning alternative fuel for CI engines, and is potentially very helpful in reducing localized urban air pollution. It can easily auto-ignite due to its very high cetane number and results in practically soot-free combustion due to easy vaporization and complete absence of carbon-to-carbon bonds (Park and Lee, 2013; Semelsberger *et al.*, 2006). Similar to hydrogen, 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 other trace gases. Synthesis gas is then converted into methanol and finally into DME by dehydrogenation of methanol (Spencer, 2011; Park and Lee, 2013). Power output of DME-fuelled engines is generally lower than diesel-fuelled engines, primarily due to significantly different vital properties of diesel and DME such as higher compressibility, and lower calorific value of DME compared to mineral diesel. Lower lubricity and viscosity of DME causes durability issues in the fuel injection system (Park and Lee, 2013). These issues therefore need to be addressed before a large-scale implementation strategy should be formulated.

Fischer-Tropsch Liquids

Fischer-Tropsch (FT) is a process which produces a variety of hydrocarbon fuels, primarily from coal or biomass. The primary product is a diesel-like fuel synthesized from syn-gas (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, the process could be termed coal-to-liquid (CTL), gas-to-liquid (GTL) or biomass-to-liquid (BTL) conversion process. The FT liquid fuel has no sulfur, almost no aromatics and a high cetane number, therefore it is an ideal diesel engine fuel. These properties make this an extremely attractive alternative fuel for CI engines (MacLean and Lave, 2003). The feedstock for BTL is biomass, which is renewable, therefore BTL can be produced from biomass residues of food crops with minimal interference with the food economy and much less strain on land, air and water resources, in comparison to alcohols or oil-seed-based fuels such as biodiesel. However, the conversion technologies such as hydrolysis and gasification are still under development (Gill *et al.*, 2011) and a significant amount of research is required before these technologies mature enough to become ready for implementation.

Alcohols

Methanol, ethanol and butanol and their blends with gasoline are used as alternative transport fuels in SI engines (Nigam and Singh, 2011; Agarwal, 2007; Balki *et al.*, 2014). Methanol is the shortest carbon chain primary alcohol, which burns cleanly due to its simple chemical structure and very high oxygen content (50% w/w). Methanol however poses an environmental hazard in case of accidental spill, because it is highly toxic and is completely miscible with water. Ethanol is similar to methanol, but it is considerably cleaner, less toxic and less corrosive (Agarwal, 2007). On the other hand, butanol is far less corrosive than ethanol and can be shipped and distributed through existing pipelines and filling stations (Nigam and Singh, 2011), however it has a very strong stench. Use of lower gasoline-alcohol blends in SI engine results in reduction in CO, HC and NOx emissions compared to baseline gasoline, while producing almost similar torque output (Agarwal, 2007; Balki *et al.*, 2014), however, aldehyde emissions increase (Agarwal, 2007). For using higher blends of alcohol in SI engines, few engine modifications are essential in order to cater to alcohol's relatively higher octane number, lower volatility, lower calorific value and different chemical reactivity *vis-a-vis* baseline gasoline (Agarwal, 2007; Kremer *et al.*, 1996). Alcohol blends can also be used in CI engines as supplementary fuel (Agarwal, 2007). For use of higher concentration ethanol blends (>20% v/v), fuel additives are essential for stabilizing the mixture and for attaining the desired cetane number (Ramadhas, 2011c). Higher percentage of ethanol in diesel requires a double injection or fumigation system, which are helpful in emissions and noise reduction but increased control complexities (Ramadhas, 2011c). Alcohols can also be blended with straight vegetable oils, biodiesel and mineral diesel (Yilmaz and Sanchez, 2012; Kumar *et al.*, 2003). Alcohol-biodiesel-diesel blends result in lower NOx and particulate emissions from CI engines (Shi *et al.*, 2006; Zhu *et al.*, 2010). Transesterification process for biodiesel production utilizes methanol/ethanol and straight vegetable oils as process inputs. This procedure of utilizing alcohol as an engine fuel is definitely preferred because aldehyde emissions and corrosion of engine parts by alcohols are not encountered in this method (Nigam and Singh, 2011).

Economic viability of bioethanol can be improved by developing more efficient enzymes, value improvement of co-products such as fructose and dried distiller's grains with soluble (DDGS), and better energy efficiency can raise the conversion efficiency; thus, reducing production cost (IEA, 2011; Kumar and Maithel, 2006). For large-scale successful implementation of bioethanol/ethanol blends, assessment of feedstock options for bioethanol production is essential and technologies for economic conversion of ligno-cellulosic feedstock to bioethanol need to be developed (Kumar and Maithel, 2006).

Straight Vegetable Oils

Plant-derived oils, waste cooking oils or waste/residue triglycerides can be converted into diesel-like fuels through several routes. Vegetable oil-based fuels are biodegradable, non-toxic and have the potential to significantly reduce air pollution. Straight vegetable oils can be used in unmodified diesel engines. However, this approach leads to several operational issues in the engines upon long-term usage. Vegetable oils have high viscosity, poor volatility and a polyunsaturated character, which adversely affects their performance as alternate diesel fuels (Agarwal, 2007; Galle *et al.*, 2012). High viscosity of vegetable oil leads to inefficient pumping and poor spray formation with larger droplet size distribution. Therefore air and fuel are not optimally mixed and combustion remains incomplete in the engine combustion chamber, leading to pollution formation. Low volatility of vegetable oils and their ability to polymerize (due to unsaturation) leads to formation of undesirable carbon deposits in the combustion chamber, injector coking and piston ring sticking (Agarwal, 2007; Galle *et al.*, 2012), which have very serious consequences in the engine. To eliminate these issues, different processes have been developed so as to make these oils adapt to modern engines. These processes (such as direct use by blending, micro-emulsion, pyrolysis, transesterification, etc.) allow the vegetable oils to attain properties closer to mineral diesel (Staat and Gateau, 1995; Desantes, 1999; Altõn, 2001). Among these, conversion of straight vegetable oils into biodiesels, which have very similar properties to that of mineral diesel, is the most accepted route (Agarwal, 2007; Gerhard, 2010) worldwide.

Hydro-Treated Vegetable Oils

Fuel with properties and composition similar to mineral diesel can also be produced by hydro-deoxygenation of triglycerides (vegetable oils). It is termed as "hydro-treated vegetable oil'' (HVO) or renewable diesel (IEA, 2011; Gerhard, 2010) or ''green diesel''. Hydro-deoxygenation is a process, in which a feedstock containing double bonds and oxygen moieties, is converted to hydrocarbons by saturation of double bonds and removal of oxygen (Gerhard, 2010). Cold flow properties of renewable diesel are superior to biodiesel but the technology for its commercial production is still in developmental stage (IEA, 2011; Gerhard, 2010).

Biodiesel

Biodiesel is a fuel, which can be produced from edible and non-edible straight vegetable oils, recycled waste vegetable oils and animal fat through transesterification process, which converts triglycerides present in vegetable oils into fatty acid alkyl esters (Li, 2004; Hamelinck *et al.*, 2004; Demirbas, 2000; Kinney and Clemente; 2005). Transesterification is the reaction of triglycerides with primary alcohols in presence of a catalyst, and this reaction produces primary esters (biodiesel) and glycerol (Agarwal, 2007). Biodiesel is the name of a clean burning mono-alkyl ester-based oxygenated fuel made from natural, renewable resources such as raw/ used vegetable oils and animal fats. Both edible and non-edible straight vegetable oils can be converted to biodiesel by transesterification. Fuel related properties of biodiesel are very similar to mineral diesel and this is amply illustrated by comparing properties of mineral diesel and Karanja biodiesel (Table 1). Carefully planned biodiesel implementation programmes in India can result in the following benefits:

- Biodiesel is a CI engine compatible fuel, which indicates the possibility of it being used as a diesel substitute with no or minor system hardware modifications. It will not lead to any significant additional cost to the existing OEMs.
- Blending biodiesel with mineral diesel can compensate for the loss of fuel lubricity in low sulfur diesel since sulphur content in diesel is being reduced continuously worldwide, in order to make them comply with EURO-IV or higher emission standards (Bozbas, 2008) and meet the requirements of new engine technologies, which are being adopted to meet these stringent emission norms.
- Utilization of biodiesel is helpful in reducing GHG emissions because vegetable oil production consumes a large part of carbon dioxide, which is consequently emitted during combustion of these fuels in the engine. Blends of diesel and biodiesel may also be helpful in reducing harmful gaseous and particulate matter emissions from the engines, which helps in meeting these stringent automotive emission norms being adopted worldwide.
- Biodiesel is a safer fuel compared to mineral diesel in its storage and handling aspects because its flash point is approximately 100°C higher than mineral diesel (Bozbas, 2008).
- It is compatible with existing infrastructure for fuel delivery, transportation and distribution of mineral diesel in blended form.
- Biodiesel can be produced from locally available biomass resources. Hence developing a biodiesel industry would strengthen local industry, particularly rural agricultural economy in agrarian countries like India.
- Biodiesel can be produced from feedstocks grown in under-utilized, high salinity lands/waste lands and will be helpful in checking soil erosion and land degradation. In the process, it also has the potential to provide livelihood for the rural poor living in areas with highly degraded lands.

For large-scale implementation of the biodiesel programme, key areas for research and development include: more efficient catalyst recovery, improved purification of the by-product glycerol for cost reduction, exploring large-scale usage of glycerol because production volume of glycerol will increase with increasing production of biodiesel, increasing shelf life of biodiesel and enhanced feedstock flexibility (IEA, 2011). With further development of technology, production of biodiesel from micro-algae based oils may reduce stress on land and water and would make large-scale implementation of biodiesel feasible (Nigam and Singh, 2011; IEA, 2011; Timilsina and Shrestha, 2011). Micro-algae can be grown in shallow water bodies, ponds as well as in shallow coastal areas, which will open up a new dimension in biodiesel production.

Though the fuel-related properties of biodiesel are largely similar to mineral diesel, there are considerable differences such as higher viscosity and density, 10-15% lower calorific value, higher/comparable cetane number, higher bulk modulus, higher oxygen content, and lower stoichiometric air-fuel ratio (Agarwal, 2007). Currently, engine control parameters are finely tuned according to fuel properties so that stringent emission norms can be complied with. Any change in fuel properties affects the optimized domain of these parameters. Optimization of an engine with respect to these fuel properties would be essential for ensuring satisfactory engine performance and emissions characteristics of biodiesel blends. Due to differences in chemical reactivity of biodiesel, suitable changes in lubricating oil composition are also essential and a new family of specialty lubricants needs to be developed for biodiesel-fuelled engines. Material compatibility of biodiesels produced from various feedstock with fuel injection equipment and rubber components of the engine also needs to be ascertained. Therefore necessary modifications in the composition of these engine components should be done before country-wide implementation of biodiesel programme (Schumacher *et al.*, 1996).

Table 1: Properties of Karanja biodiesel *vis-a-vis* mineral diesel

Property	ASTM 6571 limits for Biodiesel	Biodiesel	Diesel
Density (g/cm^3) @ 30°C	0.8-0.9	0.881	0.831
Viscosity (cSt) @ 40°C	1.9-6.0	4.41	2.78
Flash point (°C) (min.)	130	168	49.5
Cetane number (min.)	47	50.8	51.2
Conradson carbon residue (%) (max.)	0.05	0.02	0.01
Ash content (%) (max.)	0.02	0.008	0.005
Moisture content (ppm) (max.)	500	<200	<200
Calorific value (MJ/kg)	-	37.98	43.78
Copper corrosiveness	3a	1a	1a
C (%)	-	74.2	87
H (%)	-	12.9	13
N (ppm)	-	3.9	9
O (%)	-	12.8	-
S (ppm) (max.)	15	2	50

Source: Dhar, 2013

Summary and Recommendations

For ensuring adequate supply of energy for the transportation sector, a mix of several primary fuels, both alternative and conventional, is required. Utilization of non-conventional fossil resources such as natural gas, shale oil may ease the pressure on petroleum supply in the short-term, but environmental issues are also likely to get aggravated with the use of these fuel options. Biodiesel and bioethanol are currently relatively mature options; however, further improvements in their economics, environmental impact and social impact are essential. India can start moving towards these options based on the current availability of these feedstock and try to develop new production technologies for expanding feedstock base with sustainable pressure on natural biomass resources. It is expected that large-scale production of biofuels in bio-refineries would promote more efficient use of biomass and bring down associated costs in addition to enhancing environmental benefits in future. For long-term energy supply, the possibility of producing large volumes of hydrogen through distributed renewable resources like solar energy or through the bacterial route seems feasible and they should be developed as a sustainable option. Based on these discussions, the following technological and policy challenges are identified to ensure adequate supply of fuel for the surface transport sector in a sustainable manner:

- § Estimation and economic extraction of shale gas and shale oil.
- § Improvement in engine technology for more efficient utilization of gaseous fuels.
- § Modifications in engine technology to enable adopting blends of alcohol/gasoline, diesel/ biodiesel/alcohol.
- § Increasing the feedstock base for production of bioethanol and biodiesel by developing technologies forligno-cellulosic biomass utilization and algae oil production from shallow water bodies.
- § Production of methane and biomass-to-liquid (BTL) fuels, etc. from other biomass resources, which are unsuitable for ethanol production.
- § Improvement in hydrogen-fuelled internal combustion engine technology and improvement in its safety features for large-scale implementation of hydrogen as a transport fuel in future.
- § Development of technologies for hydrogen production and storage in order to ensure sustainable and adequate supply of hydrogen from carbon-neutral primary energy sources in the future.

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