# Chapter 8
# Dual-Fuel Internal Combustion Engines for Sustainable Transport Fuels

**Babalola Aisosa Oni and Samuel Eshorame Sanni**

**Abstract** The quest for a sustainable future for transport-fuels has led to the consideration of advanced methods of admixing fossil fuels without compromising their qualities; this is aimed at improving/complementing the properties of these fuels for high engine performance. Owing to the high abundance of biomass from which alternative fuels can be sourced for blending or improving the properties of conventional gasoline and diesel fuels, it has become pertinent to consider their use as complementary fuels towards ensuring high sustainability of the fuels as transport-fuels. The synergistic effects offered by these fuels helps to improve the properties of the fuels better than the individual components that make up the fuel mix. Hybrid gasoline-biofuel fuels offer these improved properties as a result of the complementary effects of either or both components offer in the hybrid fuels such that there is a boost in the fuel's combustion potential owing to the degree of homogenization attained during blending. Furthermore, despite ensuring high compatibility of the individual fuels that make up the biofuel-diesel fuel mix, it is also pertinent to emphasize the need to obtain an optimum blend of the dual fuel system for the engine performance because, for specific dual fuel systems, beyond the optimum mixture composition, the performance of the engine begins to wane owing to the alteration in the properties of the fuel mix beyond favorable conditions for complete/near complete combustion of the fuels. Therefore, in this chapter, the properties of different dual fuel systems will be discussed alongside the degree of homogenization that can improve the atomization/combustion potential of the fuels towards attaining high engine BTEs, high engine power, moderate heat release rates as well as good air–fuel ratios.

**Keywords** Alternative fuels · Combustion · Conventional fuels · Dual fuel systems · Homogenization · Sustainable transport fuels

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## 8.1 Introduction

Internal combustion engines (ICEs) convert produced heat into work from the combustion chamber. Two main ICE types such as diesel and petrol engines, contribute to environmental pollution from the release of emission from the exhausts of these engines (Lyng et al. 2018). There are about 25% of global greenhouse gas (GHG) emissions from the transportation sector as a result of higher demand in automobile (Xue et al. 2020).

Gasoline and diesel are the widely adopted fuels in ICEs/compression ignition engines (Boisen 2008). In SI engines, flame propagation occurs after an initial spark event ignites the homogeneous air–fuel mixture (Rimkus et al. 2018). Despite several decades of consistent supply and market position for diesel and gasoline as regular automotive fuels, the search for alternative fuels began to emerge in the 1980s (Das et al. 2020).

The definition of alternative fuels varies; however, it depends on the context. Alternative fuels are those fuels other than diesel and gasoline fuels, which cover a wide range of final forms and manufacturing sources (Ozcanli et al. 2018). Ethanol is an example of alternative fuel for use in spark ignition (SI) engines, irrespective of its source either from biomass or crude oil/fossil fuel. According to Arnoersson (2011), alternative fuels also include a wide class of other fuels such as non-conventional fuels (methanol, ethanol, butanol, LPG (liquified petroleum gas), Hydrogen, coal-derived liquid fuels (CTL) and pure biodiesel (B100). Some of the importance of alternative fuels can be ascribed to the following:

(i) trailing sustainable energy via increasing the consumption of alternative fuels from biomass while justifying the concerns associated with the exhaustion of energy recovered from fossil fuels (Santoso et al. 2013).
(ii) improving the efficiencies/reducing the emissions of engines by employing alternative fuels of high quality that are comparable with conventional fuels, in terms of their physicochemical properties (Manoharan et al. 2019)
(iii) .reducing the unbalanced use of traditional petroleum-based fossil fuels (Chong and Hochgreb 2011).

Despite projections that conventional fuels will continue to dominate transportation fuels for the next 5 decades, an urge for energy sustainability and a desire to cutdown greenhouse gas (GHG) emissions have caused an increase in biofuel consumption (Antunes et al. 2008). Fossil fuels significantly contribute to the emission of $CO_2$ with approximately 27 billion tons of $CO_2$ generated from anthropogenic activities per year. The use of biofuels informs a lower $CO_2$ life cycle which constitutes a significant drop in $CO_2$ emissions from a social standpoint (Kukharonak et al. 2017). Based on a life cycle assessment that was conducted to compare the greenhouse gas impacts of biofuels and gasoline/diesel fuels, the results showed that biofuels from vegetable oil gave reduced greenhouse gas emissions compared to those obtained for conventional fuels (Chintala and Subramanian 2017). The analyses considered all GHG emissions associated with their transportation, production, and storage, as well as emissions from vehicles.

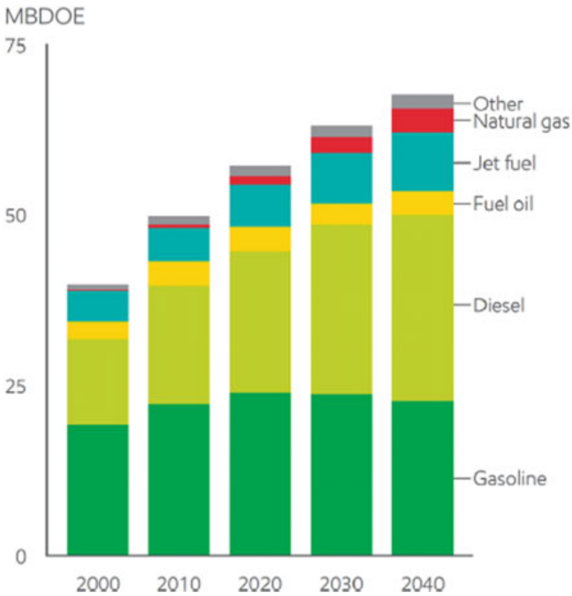


**Fig. 8.1** Global transportation demand of different fuels. Reprinted from Bae and Kim (2017) with copyright permission obtained from Elsevier

In 2012, biofuels accounted for about 4% of the total global transportation fuel. Figure 8.1 illustrates the increase in energy demand in the transportation sector where it is also noticed that the trend in the demand for biofuel also increased (Huyskens et al. 2011) which in the long run may lead to mitigation of net greenhouse emissions, thus giving rise to low-carbon transportation fuels; this also informs an expected reduction in the emission of GHG in the nearest future (Heffel 2003).

In addition, it is critical to understand whether a fuel is renewable energy-based such as those sourced from crops, because when they burn, they only marginally increase the levels of $CO_2$ in the atmosphere, hence the need to understand the clear distinction in the origin of these fuels as to whether they are generated from biofuels or fossil. Figure 8.2 is an illustration of several fuels that can be sourced from different origins.

## 8.2 Different Biofuels and Their Blends for Transportation

### *8.2.1 Dual Fuel System*

A dual fuel engine operates on diesel (B100) or the mixture of natural gas and diesel, distributing the same engine torque curve, transient response and power density as the

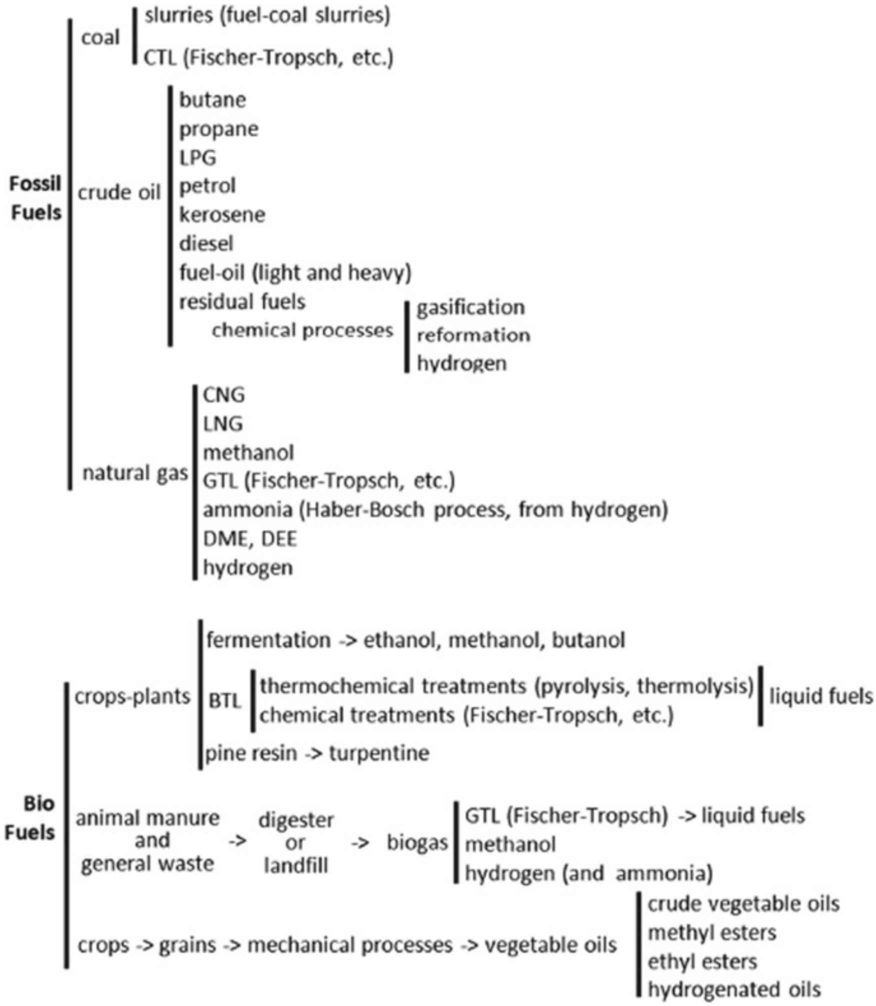


**Fig. 8.2** Types of fossil and biofuels that can be used in ICEs. Reprinted from Martins (2020) and Martins and Brito (2020)

base diesel engine. The transportation sector is the largest oil consumer accounting for about 53% of total oil/fuel-consumption (Åhman 2010). Hence, there is a crucial demand for sustainable fuel in the transportation sector. The current trend of fossil fuel as means of transportation increases the tendencies for high GHG crisis. Several studies are being currently conducted on the aforementioned and much emphasis is being placed on alternative fuels that would provide similar effects as gasoline on a long-term/large-scale basis as transport-fuel (Banerjee et al. 2017).

#### 8.2.1.1 Recent Works on Dual-Fuel System Based-Engines

Biofuel is a vehicle alternative that has the potential to significantly minimize engine emissions and improve air quality. Biofuel production and their uses have increased dramatically in recent years around the world. Some countries have made biofuel consumption a goal and mandate. Elfasakhany (2018) carried out an experiment on bio-methanol blended with gasoline and iso-butanol and gasoline (A), and bio-ethanol blended with the admix of gasoline and n-butanol (B) at 3–10 vol% biofuels. The 2-ternary fuels (A and B) were compared with gasoline in terms of emissions and efficiencies in a gasoline-fueled engine. The results show that the A and B fuel blends showed appreciable efficiencies and better emissions than the gasoline fuel. Oni et al. (2021) blended neem and camelina biodiesel methyl esters at different ratios in a 1.9 Multijet diesel engine. The experimental result shows an increase in BTE with lesser carbon monoxide, hydrocarbons and $CO_2$ emissions with higher NOx emission as compared to the conventional diesel fuel.

Elfasakhany (2021) blended methanol, acetone, i-butanol-n-butanol, and ethanol biofuels, in single/dual modes in SI engine. All the analyzed biofuels were compared with each other as well as with neat gasoline in a SI engine. The improvement of methanol in the SI engine was similar to that of ethanol, although methanol is poisonous, which makes it not compatible with SI engine. I-butanol and n-butanol biofuels, showed less engine performance with higher emissions of CO and HC. Methanol and ethanol showed the highest engine performance, with higher carbon dioxide emissions. The engine performance of acetone was moderate, with very low emissions of HC and CO when compared with other biofuels. Different dual biofuel blends of ethanol–methanol was found to be more superior in terms of engine efficiencies and low emissions than the blends of i-butanol–n-butanol and ethanol-i-butanol.

#### 8.2.1.2 Projects Underway for Dual Fuel-Based Systems Engine Applications

Fuel pilot-injection, which includes Dual-fuel technology and a High Pressure Direct Injection (HPDI) method, is a well-known type of ignition assist. Dual-fuel engines, have high NOx and $CH_4$ emissions as well as low efficiency, especially at 50% load condition, while the HPDI technology has particulate matter emissions from natural gas diffusion flames. This HPDI injector can be used to inject (CNG) and $H_2$ compressed natural gas (Juknelevičius et al. 2019). This (HPDI) injector consists of two-concentric spring-loaded needles, thus allowing gas and liquid fuels to flow simultaneously.

Port injection can be used to inject methanol into the intake port, then directly injecting diesel near the TDC to ignite the mixture of methanol/air. Wu and Han (2020) studied the effects of intake-air temperature and the mass fraction of methanol on a six-cylinder turbocharged diesel engine. There was a decrease in the intake-air temperature which in turn reduces the EGT and indicated thermal efficiency, thus increasing the methanol energy fraction in a dual-fuel operation mode.

### *8.2.2 Biomethane CNG Hybrid*

One of the several alternatives for the transportation sector is biomethane-CNG hybrid. Methane is the main composition of biomethane. It is produced by anaerobic decomposition of organic matter via biomass gasification or by bacterial decomposition. To supply vehicles with biomethane, the gas must be compressed to about 200 bars (Boesel 2009) prior being mixed with CNG. This combined hybrid fuel is one of the most promising fuels for achieving a carbon–neutral environment, with a significant reduction in the 'Well to Wheel' emissions of any wheel Baldwin system; this mixture is also referred to as the green energy equivalent of methane (Arnoersson 2011).

Raw biogas is primarily composed of $CH_4$ and $CO_2$, with average concentrations ranging from 60–75 and 35–60%. Upgrading raw biogas to a highly purified biomethane can give about 98% $CH_4$. Pressure swing adsorption, water scrubbing, and amine absorption are the common approaches adopted in attaining high purity of the gas (Zhang et al. 2019a). Upgraded biomethane can be applied in two ways i.e., by compressing it to 200 bars or cooling it to a liquid at 162 °C (liquefied biogas-LBG). To liquefy biomethane, an additional polishing step is frequently required, in which the biomethane is purified further. Kaiser and White (2009) compared various upgrading methods for compressed biogas and liquified biogas, and their method of distribution, the result showed that liquified biogas needs more energy when compared to compressed biogas, however, liquid biogas (LBG) has lower global warming impacts relative to compressed biogas (CBG) due to their reduced $CH_4$ slips (Obermair et al. 2010). Biogas produced from waste matter is a good potential alternative gaseous energy fuel for ICEs, and it has the potential to replace fossil fuels.

When compared to gasoline, the use of biomethane-compressed natural gas hybrid in the transportation sector can contribute to lowering GHGs by about 80% (Bordelanne et al. 2011); biomethane is essentially biogas that has been purified to make it of high-quality natural gas. Biomethane is a non-$CO_2$-emitting biogas that is 98% $CH_4$ with mixed proportions of $C_2H_6$ which helps to increase its calorific value (Zheng et al. 2012).

It is impossible to use a biogas-CNG blend in a CNG vehicle unless the biogas quality is improved. Biomethane is an improved biogas that is used as a fuel in CNG vehicles. CNG vehicles emit approximately 17% less GHG than gasoline vehicles (Zhang et al. 2019b). When compared with gasoline, vehicles running on biomethane-CNG blends can give reduced emissions of about 51%. Toyota Prius CNG Hybrid prototype powered by biomethane reduces emissions by 87% when compared to gasoline vehicles (Wellinger and Lindberg 2000).

Energy crops, residential, industrial waste, solid waste, forest residue, agricultural residues etc., are raw materials used to produce short-term synthesis of biomethane (You et al. 2020). Energy crops are good options for medium term production of these fuels, while biomass gasification from lignocellulosic resources is usually employed for long term purposes (Bordelanne et al. 2011; Stenlåås et al. 2004). Biomethane needs additional processes to work in a vehicle so as to prevent engine corrosion.

Biomethane can be produced from—wet materials (as in anaerobic fermentation) or dry materials (as seen in gasification processes) (Bordelanne et al. 2011; Salazar et al. 2009). The production of biomethane via biogas is susceptible to pH, type of feedstock, temperature, moisture content, digester technologies, type of bacteria used etc. (Liu and Dumitrescu 2019). Biomethane can also be produced from gasification of woody biomass. New gasification technologies are currently ongoing to improve the production of biomethane. The first is indirect gasification which is suitable for small scale (< 100 MW) (Lee et al. 2001, 2013). The second is the use of fluidized bed gasification (FB) which is suitable for large scale (> 100 MW) plants (Åhman 2010). The advantage of this process is that it can be used with a variety of feed stocks. Biomethane is a high-quality energy carrier that can be used in varieties of applications and it is highly efficient. Furthermore, biomethane can be used for transportation, which can therefore be integrated into the existing natural gas distribution network (Åhman 2010).

## 8.3 Biogas-Biodiesel Fuel Mix for SI Engines

Small co-generation systems are almost always attributed to the use of spark ignition engines that run directly on biogas (with impurities like water, carbon dioxide, or hydrogen sulphide). The conversion of SI engines to make them compatible with gaseous fuels, is simple, however, it only requires the installation of a simple gas-fuel adaptor and probably toughened valves and valve seats (Yang and Zeng 2018; Lebedevas et al. 2019). The articles published for biogas-powered spark ignition engines primarily include works on the engines' overall emission and performance relative to when the system is fueled with gaseous and liquid fuels. More on this will be discussed in the later sections. Furthermore, quite a number of studies with and/ or without computer simulation have been discovered in the literature for gaseous fuel systems. Almost all of the investigators used simulated biogas instead of raw biogas, with typical composition of methane (~60%) and carbon dioxide (~40%) in their studies (Glaude et al. 2010). Other studies have also shown that, biogas being a dilute gaseous fuel may have substantial effects on the engine's combustion, emission and performance characteristics (Lee et al. 2001; Adelt et al. 2011; Matthias et al. 2012). Table 8.1 shows the properties of single fuel systems that can be blended as fuels for SI engines.

**Table 8.1** Properties of different single gaseous fuels

| Parameter | Unit | Natural gas properties (* $10^{-1}$) | Town gas (typical properties) (* $10^{-1}$) | Biogas properties with: $CH_4$ (60%), $CO_2$, (38%, other gases (2%) (* $10^{-1}$) |
|---|---|---|---|---|
| Theoretical air requirement | $m^3$ air/$m^3$ gas | 95.3 | 38.3 | 57.1 |
| Calorific value (Lower) | $MJ/m^3$ | 361.4 | 161 | 214.8 |
| Max. ignition velocity | m/s | 3.9 | 7.0 | 2.5 |
| Dew point | °C | 590 | 600 | 600–1600 |
| Density | $kg/m^3$ | 8200 | 5100 | 12,100 |

Adapted from Huyskens et al. (2011)

### *8.3.1 Potential Single Fuel Systems that Can Be Blended and Their Characteristics*

See Table 8.1.

### *8.3.2 Dual Fuel Blending Techniques: Methods of Preparation, Homogenization and Their Selection Criteria*

ICEs powered by CNG are used in industries. Compressed natural gas engines have many advantages over diesel and gasoline combustion engines. In the lean operating region, CNG engine performance can be improved (Salazar and Kaiser 2011). Conversely, very low flame increases the CNG velocities and severely limit the lean operating limits of compressed natural gas engines. $H_2$ has a fast flame speed and a wide operating range that includes lean conditions. The addition of hydrogen to a compressed natural gas engine makes it a feasible and cost-effective method of extending the lean operating limit, improving performance and lowering emissions (Scarcelli et al. 2011). However, $H_2$ has some shortcomings as fuel source such as low power density as a result of low-heating value per unit volume when compared to compressed natural gas, as well as gas susceptibility to pre-ignition and engine knock due to low minimum ignition energy and wide flammability limits (Sandalcı and Karagöz 2014). Thus, combining $H_2$ and compressed natural gas brakes the limitations of each fuel-type.

Researchers have conducted experiments on alternative fuels that can be blended with gasoline fuels. ICEs also use alternative fuels such as natural gas, $H_2$, ethanol,

**Table 8.2** Fuel properties of acetylene, hydrogen, CNG, gasoline and ethanol

| Properties | Acetylene $*10^1$ | $H_2$ $*10^1$ | CNG $*10^1$ | Ethanol $*10^1$ | Gasoline $*10^1$ |
|---|---|---|---|---|---|
| Formula | $C_2H_2$ | $H_2$ | $CH_4$ | $C_2H_5OH$ | $C_4 - C_{12}$ |
| Density (kg/m$^3$) | 0.11 | 0.0081 | 0.07 | 81.0 | 70–75 |
| Ignition temperature (°C) | 30.5 | 57.2 | 54.0 | 36.3 | 25.7 |
| Motor octane number (MON) | 4.5 -5.0 | 13.0 | 10.5 | 90.0 | 9.7 |
| Flammability limit in air (vol%) | 0.25–8.1 | 0.4–7.4 | 0.53–1.5 | 0.3–1.9 | 0.14–0.76 |
| Minimum quenching diameter (mm) | 0.09 | 0.09 | 0.35 | 0.30 | 0.30 |
| Maximum flame speed (m/s) | 0.15 | 0.35 | 0.04 | 0.06 | 0.05 |
| Lower heating value (kJ/kg) | 4825.5 | 12,000 | 5000 | 2700 | 4300 |
| Adiabatic flame temperature (K) | 250 | 240 | 233 | 209.3 | 231.0 |

*Source* Adapted from Karim and Wierzba (1992) (no need for copyright, values were modified)

biofuels and acetylene (Oni et al. 2021; Saravanan and Nagarajan 2008). Hydrogen is approximately fourteen times lighter than air in the gas phase. Moreover, it is the cleanest fuel on the planet. Due to its high ignition limit (5–76%) and low ignition energy, it requires a special design to be used in its pure form in ICEs. It has been demonstrated that adding 20% hydrogen to fuels improves the fuel's emission, performance, and combustion characteristics. Natural gas is primarily composed of $CH_4$ (85–96%) which can be used as fuel in ICEs. In ICEs, pure ethanol can be admixed with other fuels or used as fuel alone. NG, hydrogen, NG + $H_2$ (HCNG), ethanol, ethanol + gasoline, ethanol + $H_2$, acetylene, acetylene + gasoline mixtures have all been studied for their effects on engine emission and performance characteristics (Oni et al. 2021; Kaiser and White 2009).

To reduce emissions from ICEs, the properties of acetylene, $H_2$, ethanol, and NG which are alternative fuels that can be used without changes in SI engine modification, and their effects on the emission and performance of the engine, have been studied. Table 8.2 shows the chemical and physical properties.

### *8.3.3 Conditions for Maximizing the Combustion Potentials of Dual Fuels in ICEs*

As shown in Table 8.2, $H_2$ has distinct physicochemical properties when compared to diesel, CNG, and gasoline commonly used as transportation, fuels. The engine performances involving these fuels in various engine-modes are comparable to that of $H_2$ for the same engine types. One benefit of using $H_2$ in internal combustion engine as a clean alternative fuel is that it contains no carbon (Murphy and Power 2009). This means that carbon-based emissions, primarily carbon dioxide, carbon monoxide and soot can be completely removed leaving NOx gases. Because of its high energy density, $H_2$ can provide almost 3-times as much energy by mass as diesel, CNG, and gasoline fuels as evidenced by its lower heating value. In lieu of the aforementioned, there are lots of limitations associated with $H_2$ owing to its extremely low density (Karim and Wierzba 1992). Due to the extreme low molecular weight of $H_2$, its temperature and density at atmospheric pressure are in an order of magnitude that is less than that of NG. Because of its low boiling point, compressed hydrogen is likely to be the most popular storage option. Due to limited vehicle space, this poses a challenge for the implementation of $H_2$ in ICE on-road applications. In order to increase hydrogen density as well as its volumetric energy content, the storage pressure of the gas must be increased (Mansor et al. 2017). For example, at 370 bar and 273 K, the density of hydrogen can increase to 32 kg/m$^3$ and its volumetric energy content can be as high as 3800 MJ/m$^3$. $H_2$ is expected to be highly resistant to knocking as a result of its high auto-ignition temperature and RON, 130 in comparison to other common fuels. However, it has a lower minimum ignition energy in air of stoichiometric requirement than hydrocarbon fuels, thus indicating that $H_2$ can be ignited easily by hot spots in the chamber (Chu et al. 2018). This can result in fuel pre-ignition, which is defined as combustion during the compression stroke prior to ignition. This causes knock, loss of combustion phasing control and, failure in engine. However, the global effects of knock and pre-ignition cannot be distinguishable (Ehsan et al. 2003), owing to the fact that pre-ignition leads to knock. Previous works have shown that MON of $H_2$ is much less than its RON, compared to a normal 8.0–10.0—point reduction for gasoline; although the exact value of $H_2$ MON has not been clearly understood, nonetheless, MON is confirmed to be a more accurate knock resistance metric in $H_2$ engine designs (Dimitriou and Tsujimura 2017). This explains why knock is frequently reported in $H_2$ engine applications. In comparison to conventional hydrocarbon fuels, hydrogen has a short quenching distance. As a result, higher temperature-gradients close to the walls of the chamber are to be expected which may result in higher heat losses. When $H_2$ is applied in engines, the short quenching distance combined with the high flame speed in air, indicates a greater proclivity for flame backfiring into the intake manifold. This problem can be solved by changing the engine geometry, and completely eliminating abnormal discharge in the ignition system.

Hydrogen's unique physical and thermochemical properties can aid in the design of highly efficient ICEs. This is because, the dispersion of $H_2$ is 4-times faster than compressed natural gas, as evidenced by comparing their diffusion coefficients in air (Baldwin 2008). In ICEs, this can promote air mixing and in-cylinder fuel. The volume fraction of the required stoichiometric hydrogen is 29.43 vol%. Nonetheless, the wide flammability limit of 4–76 vol% $H_2$ in air, combined with the high flame speed, implies that the use of $H_2$ in internal combustion engines can give rise to significantly lean fuels and enhanced thermal efficiencies (Adelt et al. 2011). In stoichiometric amounts, the adiabatic flame temperature of hydrogen is relatively high, which promotes NOx formation. Nevertheless, due to the wide flammability limits or lean operations, a high level of EGR can be used to reduce NOx emissions (Hänggi et al. 2019). The use of $H_2$ in internal combustion engines may raise additional safety concerns regarding the on-board fuel storage and delivery system, especially when high pressure hydrogen is used (Ogunkunle and Ahmed 2019).

## *8.3.4 Factors Effecting Dual Fuel Characteristics in SI Engines*

### 8.3.4.1 Effect of In-Cylinder Pressure

The presence of the water/carbon dioxide that is inherent in biogas results in a reduction in the in-cylinder pressure (Fig. 8.3a) and the rate of pressure rise. When the diluent concentration increases, the delay in the position of maximum combustion pressure occurs (Szwaja and Grab-Rogalinski 2009). This can possibly be clarified in terms of low burning velocity, lean mixture, low energy input per cycle, and variations in mixture strength. However, higher compression ratios (CRs) can significantly improve the cylinder pressures. According to the works of Kalsi and Subramanian (2017), an optimal CR of 13:1 for a biogas mixture is achieved for biogas containing 40% carbon dioxide but can be reduced above 40% concentration thus causing reduction in the engine efficiency.

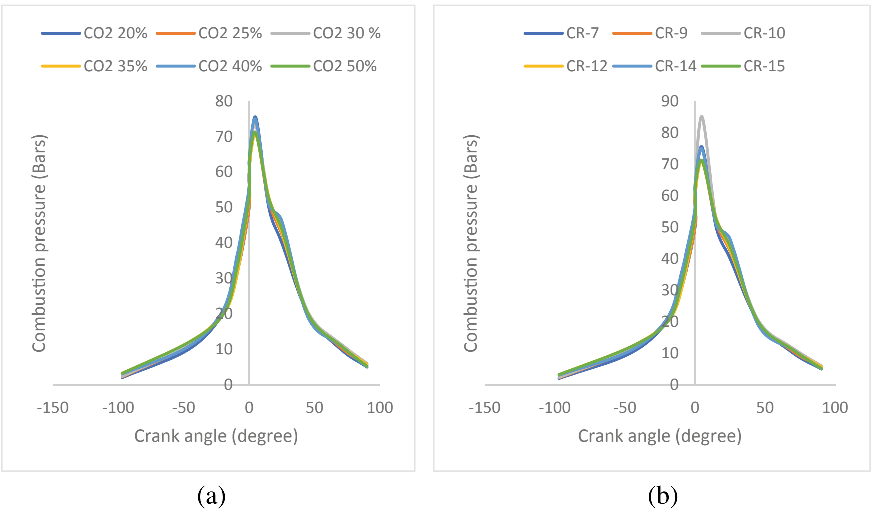


**Fig. 8.3** **a** Cylinder pressure versus crank angle for different $CO_2$ fractions in biogas, speed 2000 rpm, 15:1 and A/F = 0.98 (the lowest peak for the highest $CO_2$ content); Fig. 8.3 **b** Cylinder pressure versus crank angle for different Compression ratios at 2500 rpm, A/F = 0.97 and $CO_2$ fraction in biogas = 37.5% (the lowest peak for the lowest)

#### 8.3.4.2 Effect of Air–Fuel Ratio

The occurrence of carbon dioxide in biogas reduces the level of flammability of the air/fuel ratio. Air–fuel ratio decreases as the $CO_2$ level in fuel rises (Helmolt and Eberle 2007). The engine operating point shifts away from the stoichiometric mixture and towards the weak-mixture flammability limit with high $CO_2$ content, and the combustible mixture range becomes more sensitive to the mixture's velocity level and turbulent characteristics of the mixture to be burnt (Stürmer 2017). Ambarita (2017) calculated the highly combustible air- fuel ratio range for various fuel proportions. The authors stated that as the carbon dioxide concentration in biogas improved, the carburetor itself made the mixture weaker. Because $CO_2$ is less dense than $CH_4$, thus lowers the volumetric flow rate of fuel upon induction. The occurrence of diluent $CO_2$ in biogas has a serious influence on the spreading of flames into the flowing streams of fuel/air mixtures in SI engines. Because the specific heat of $CO_2$ tends to increase at a faster rate as temperature rises; also, its share of the fraction of energy released by fuel oxidation rises at elevated temperatures (Roubaud and Favrat 2005). At such high temperatures, $CO_2$ will undergo high endothermic dissociation reactions. As a result of the presence of $CO_2$ in biogas, the net effect is a significant reduction in the adiabatic flame temperature of the biogas (Bortel et al. 2019). Because of the reduction in diffusivity, rate of reaction, flame temperature, and transport phenomena of the mixing properties, both laminar and turbulent burning velocities decrease significantly. Yadvika et al. (2004) calculated the mass fraction burnt using a 2-zone combustion model. The model was modified to fit the combustion geometry of diesel engine under consideration thus making it easy to compute the turbulent burning velocities. The authors discovered a 50% significant decrease in turbulent burning velocity with a biogas mixture of 70% $CH_4$ and 30% $CO_2$ as compared with 100% $CH_4$. Lower flame propagation rates result in a significant increase in the length of the period of combustion, which increases as the $CO_2$ in biogas increases (Stockhausen et al. 2002). In biogas combustion, the MBT timings are typically more sophisticated. Verma et al. (2018) investigated the effect of $CO_2$ dilution in biogas on the burn durations/periods and MBT timings using a SI engine model. The authors discovered a highly developed MBT timing as well as higher (i.e., 10 and 90%) mass-fraction burn durations for biogas. To compensate for these negative effects and achieve optimal engine performance, biogas spark timing should be advanced compared to natural gas or gasoline.

#### 8.3.4.3 Effect of Power and Fuel Consumption

In comparison to natural gas or methane, the diluent $CO_2$ in biogas lowers the calorific value of the fuel which in turn reduces the brake power output (BPO) and increases the Brake specific energy consumption. The published engine power data for biogas fueling shows a wide range of variations. The large differences in power output are caused by differences in ignition timing, engine specifications, and operating air–fuel ratios. Midkiff et al. (2001) found that biogas (60% $CH_4$: 40% $CO_2$) reduced the

BPO by 14% at ER = 1 when compared to the baseline fuel natural gas. The BSEC increased as the carbon dioxide content of the fuel increases, thus signifying that dilution has no effect on brake specific energy consumption with ER or φ ranging from 0.7 to 0.9. This could be because, at lower equivalence ratios, air becomes a more dominant diluent than $CO_2$ in biogas. Depending on the operating conditions and engine configurations, the reduction in power output compared to methane or natural gas ranges from 3 to 22%. According to Anwar et al. (2019), such a large reduction in power output in the case of biogas fueling could be due to incorrect optimization of the ignition timing and air/fuel ratio. For example, Lebedevas et al. (2019) did not optimize biogas ignition timing, and the $CH_4$ flow rate remained unchanged when $CO_2$ was added. This led to a higher ER and a 20% decrease in output power. Suarez-Bertoa et al. (2019) tested stoichiometric air–fuel ratios with a fixed ignition timing (12° BTDC). They discovered a 2% decrease in output for every percentage point increase of $CO_2$ in the biogas. However, Wimmer et al. (2005) discovered a 9% decrease in power output when switching from $CH_4$ to biogas in stoichiometric amounts. This was done with a predetermined equivalence ratio (ER). This reduction was discovered to be primarily due to a decrease in entrained energy on the inside of the cylinder, as well as a partial increase in combustion duration (White et al. 2006).

#### 8.3.4.4 Effects of Diluent

Biogas is mostly methane, which is an exceptional fuel for spark ignition engines due to its high resistance to knock and auto-ignition. This means that the engine can function at a broader range of compression ratios and that the biogas will not cause unexpected knocking. The amount of $CO_2$ tends to lower the mixture temperature which in turn reduces the burning velocity, however, this does not increase the knocking tendency for most engines and operating conditions (Scarcelli et al. 2011; Yadvika et al. 2004). Salazar and Kaiser (Niculescu et al. 2017) calculated the effect of diluents in a fuel/$CH_4$ on incidence of knock. Knock would occur, according to the model, when the energy generated by the end gas's pre-ignition reaction activity ahead of the spreading flame gets strong enough to cause auto-ignition (Mohammadi et al. 2007). The results revealed that the increased diluent in biogas inhibited the pre-ignition reaction of the end gas region, thus suggesting low knock relative to the pure fuel $CH_4$ mixture under the same process conditions.

#### 8.3.4.5 Effects of Engine Emissions

Nox

Nitrogen oxide (NOx) formation is strongly influenced by the engine's combustion temperature and $O_2$ concentration. The combustion temperature is lower in leaner mixtures, but the $O_2$ concentration is higher. On the other hand, as the mixtures become more concentrated stoichiometrically, the combustion temperature rises to its maximum, but the $O_2$ concentration falls (Meijden et al. 2011). As a result of the following competing effects, most HC fuels emit their highest NOx gases at just below the critical stoichiometric amount of air required for the operation (Maggio et al. 2019). NOx emissions are reduced via any method that lowers the combustion temperature. However, diluents in $CH_4$ lowers the combustion temperature, biogas combustion emits less NOx than NG or gasoline. Various researchers have obtained similar results. Midkiff et al. (2001) discovered a decrease in NOx for all biogas mixtures when compared to the NG they used. Peak NOx emissions from biogas, between the range of 0.85–0.9, showed 50% reduction. Anwar et al. (2019) conducted an analytical study on the formation of NOx emissions from biogas and discovered that they are lower than $CH_4$ emissions. The researchers explained the cause to be the existence of lower burnt gas temperatures caused by inert gas dilution in the biogas. The burnt gas temperature was found to be reduced by 130 K when compared to $CH_4$, which was enough to cutdown the NO level in the exhaust by half. The peak value of the equilibrium predicted NO was found to be at par with the actual value received at the exhaust according to the results of the simulation (Shrestha and Karim 2001). However, the peak value of equilibrium predicted NO was found to be higher than the initial kinetically predicted value, and the kinetically predicted concentration of NOx value was found to be higher than the equilibrium towards the end of combustion process. According to Kalsi, (Kalsi and Subramanian 2017), higher compression ratios increased the NOx emissions in contrast to the perceived lower compression ratios. But the peak NOx for biogas was still lower than that obtained for Natural gas (NG) of the highest composition (35%) relative to those of 10 and 25% NG respectively.

### CO and $CO_2$ Emissions

CO emissions from biogas are found to be low in lean mixtures and do not vary with the $CO_2$ fraction in the mixture. CO emissions for a biogas mixture (60% $CH_4$, 40% $CO_2$) are found to be approximately 10% higher than NG for the leaner mixtures ($\varphi = 0.65$–0.90). Because $O_2$ becomes scarce as the mixtures are enriched, CO emissions rise rapidly with the $CO_2$ fraction due to incomplete combustion (Bhattachariya 2004). Bari (1996) also suggested that high CO emissions from biogas appeared to be linked to lower exhaust temperatures rather than with fuel $CO_2$ dissociation. According to the Bhattacharya et al. (Bhattachariya 2004) investigation, the higher the $CO_2$ fraction in biogas, the lower the exhaust temperature, and the end result is higher CO emissions in the exhaust. Increase in carbon dioxide emissions is directly proportional to the amount of $CO_2$ in biogas. Feroskhan et al. (2018), on the other hand, reported that with mixtures richer than the required stoichiometric amounts of air and fuel, the increase in $CO_2$ emissions can be modified by dissociation reactions which lead to an increase in CO emissions. Also, according to reports, the results from the emissions of $CO_2$ can be up to about 80% more than that of natural gas for the biogas (Adelt et al. 2011).

Unburnt HC

Unburned HC emissions have been reported to be higher in biogas compared to natural gas, and they increase as the fractions of $CO_2$ in the biogas mixtures increase (Chang et al. 2011). The dominant parameters causing increased HCs in leaner mixtures are quenching effects due to lower cylinder temperature and incomplete combustion due to slower flame speed. Incomplete combustion occurs in richer mixtures due to a lack of high $O_2$ concentration, resulting in increased hydrocarbon emissions (Caton and Pruitt 2009) (Table 8.3).

### *8.3.5 Dual Fuel Systems and Engine Life*

Only a few research articles have been published that investigated the impact of biogas fueling on engine life. Barik and Murugan (2016) looked into the severe corrosion of biogas-powered engines that failed after 1000–3000 h of operation. The failure of the small end and camshaft bearing (especially copper-based) was nearly always found to be the cause of failure due to $H_2S$ attack. In the study, the formation of blowby, its composition and flowrate were measured, modeled, and simulated using a simple computer program. The simulation revealed that the complex nature of the quenching process in the combustion chamber affected the fuel content of blowby. According to Di Iorio et al. (2017), the $H_2S$ attack could only be caused by unburnt fuel entering the crankcase and the rate of ingress increased as the operating hours of the engine increased. It was also suggested that copper-based bearings should be avoided or protected by a positive flow of engine oil (Wallner et al. 2009). During their investigations into biogas-powered vehicles, other researchers made similar findings as listed below:

- SI engines tolerate emission level of hydrogen sulphide up to 1000 ppm.
- between 1000 and 2000 ppm concentrations of $H_2S$ the acidification problem can be controlled (Tanoue et al. 2000).

Tanoue et al. (2000) studied the effect of adding a minute quantity of $H_2$ to the lean $CH_4$ mixture. The burning velocity significantly increased as it were for the misfire limits, which were the main disadvantages of using biogas fuel. Verhelst (2014) used unscavenged combustion pre-chamber instead of a direct ignition type to achieve a cleaner and more rational biogas while incurring no significant economic costs. When compared to NG operation, CO and total hydrocarbon (THC) emissions were reduced by 15% and 8%, respectively, for the same rated power output and NOx emissions. Alternatively, efficiencies greater than 36% were achieved while the combustion process remained essentially unchanged (Wallner et al. 2013).

**Table 8.3** Summary of some biofuel types, their engine emissions, combustion characteristics and performance

| Fuel/experimental details | BTE | NOx | UHC | CO | $CO_2$ | Smoke | Ignition delay | Rate of heat release | References |
|---|---|---|---|---|---|---|---|---|---|
| D90B10; D80B20; D50B50; D95E5; D90E10; E15D85—Cottonseed Biodiesel | Slightly higher | NA | Decreases | Decreases for all blends Increases with the percentage of biofuel in the blend | Decreased | Decreases substantially with increase in bioethanol | Increases with increase in ethanol | Very high at the start of combustion and lower later on the expansion stroke for diesel/Biodiesel blends | Tutak et al. (2016) |
| Diesel–Methanol dual-fuel—Separate injections | Increases with methanol content in the blend | Decreases significantly | NA | Decreases | NA | Decreases | NA | NA | Bharadwaz et al. (2016) |
| B10E10D80—Biodiesel obtained from microalgae oil Variable compression ratio diesel engine at different speeds | A maximum BTE of 28.2% was observed | Decreases | Decreases | Decreases | Decreases | NA | NA | NA | Niculescu et al. (2017) |

(continued)

**Table 8.3** (continued)

| Fuel/experimental details | BTE | NOx | UHC | CO | $CO_2$ | Smoke | Ignition delay | Rate of heat release | References |
|---|---|---|---|---|---|---|---|---|---|
| D90M10; D80M20; D70M30 | NA | Decreases with an increase in the percentage of methanol in diesel blends | NA | NA | Decreases with the increasing percent of methanol | Increases with an increase in the percentage of methanol in diesel blends | Higher at all loads | The maximum value increases with increasing the methanol fraction in the blends | Bae and Kim (2017) |
| Ethanol/Isobutanol as additive in the biodiesel/diesel blends – Fish oil Biodiesel | Higher | Increased | Decreased | Decreased | NA | Decreases | NA | NA | Paredes-Sánchez et al. (2019) |

*D* diesel; *B* biodiesel; *E* ethanol, *M* methanol

### 8.3.6 *Current Trends in the Use of Biofuels as High-Performance Engine Fuels*

Since the current body of literature is largely flooded with works related to CI engines relative to ICEs (very scarce), it is common knowledge that same fuel systems can be modified with compatible properties for ICEs. Also, most of the fuel proportions adopted for CI engines are not usually desirous below or above the optimum composition, however, it is then recommended that some of the fuel misfits can be tried for their compatibilities with ICEs.

In dual mode, $CH_4$ and diesel combustion occurs in 3-modes: flame progression in methane–air mixture, pilot diesel combustion, and $CH_4$ combustion around the diesel spray. Exceptionally poor blends, increase the flame zones, and incomplete combustion of the fuel for all three sections at minimum loads which can lead to an increase in hydrocarbon and carbon monoxide emissions (Prakash et al. 1999).

Homogeneous charge compression ignition engines may be the ultimate solution to lowering NOx, since they emit almost no NOx. They have the advantages of diesel and Otto engines. Homogeneous charge compression ignition engines have many benefits, such as high thermal efficiencies, low emission, and high heat release rates, due to the premixed and lean mixtures, self-ignition at high compression rates (Mohammadi et al. 2007). It has some disadvantages such as difficulty in controlling the starting point of ignition over variations of speed. The combustion phase has been controlled with variable valve timing and EGR to overcome this HCCI challenge. The most effective way to control combustion, however, is to inject pilot diesel.

Meijden et al. (2011) transformed a heavy-duty compression ignition engine to dual-fuel by injecting a diesel and NG mixture into the compression ignition engine and injecting small amounts of diesel near TDC. In that study, a heavy-duty engine is transformed to dual fuel operation.

Baldwin (2008) investigated the effects of dissolved $CH_4$ in diesel fuel on engine emission and performance in a single-cylinder direct-injection diesel compression ignition engine. They discovered that as methane concentration increased, the maximum heat release rate decreased while the ignition delay increased. Diesel fuel containing dissolved $CH_4$ emits less NOx, and the amount of smoke produced is proportional to methane concentration.

Chong and Hochgreb (2011) injected 60% methane and 40% carbon dioxide by volume into the intake manifold of an engine. Their findings show that particulate matter (PM), smoke, and NOx, levels decreased, however, the combustion stability was compromised, and then the resulting carbon dioxide and HC emissions were seen to have increased. As a result, they introduced syngas to the liquid in attempt to optimize combustion stability emissions.

Oni et al. (2021) investigated the combustion, performance, and emission characteristics of moringa biodiesel as an additive in (HCNG). According to the authors, five hybrid HCNG—Moringa biodiesel (MB) oil samples were analyzed in a (Petter PH1W diesel engine). At higher engine loads, there was improvement in the engine performance between 19 and 33.9% for all the fuel blends which confirms the suitability of MB as an additive for improving the BTE of the engine with reductions in HC, $CO_2$, CO, and NOx emissions.

## 8.4 Future Prospects of Dual-Fuel System as an Alternative Fuel

The transition to a 100% renewable energy system is a complex process which may be saddled/fraught with technical and economic difficulties. To achieve these goals, several steps should be taken concurrently, including increasing the energy efficiency, reducing primary energy consumption, and deploying variable energy sources (Wallner et al. 2009). This transition by the energy sector channeled towards decarbonization necessitates the use of new technologies and energy sources (Suresh et al. 2018). Increased use of renewable energy sources necessitates the installation of energy storage systems to store excess electricity and improve system efficiencies (Rimkus et al. 2018). These electricity surpluses, which will become more common in the future energy systems, could be effectively used to produce alternative fuels. The majority of the alternative fuels being considered for future applications are already known chemicals or products that are currently used for other purposes (Lee et al. 2001). Another significant benefit of some alternative fuels is their ability to serve as an energy-carrier. This feature may be critical when discussing their potential for use and future development. Fuels that can be used for both power generation and as an energy carrier will play a larger role in the future and are likely to be used on a larger scale (Mansor et al. 2017). Renewable energy sources, on the other hand, such as biomass, are already widely used, and their roles in future systems are unquestionable despite the fact that a significant increase in biomass consumption raises serious concerns about its sustainability and necessitates the development of new approaches (Huyskens et al. 2011). Figure 8.4 shows some renewable energy sources as potential sources for sustainable biofuel production.

## 8.5 Sustainable Technologies for Alternative Fuels and Future Challenges

### *8.5.1 Sustainable Technologies*

#### 8.5.1.1 Production of $H_2$ for CNG Fuel-Systems

Production of $H_2$ from fossil fuels is a common process that uses coal or natural gas as feedstock (Stančin et al. 2020). $H_2$ is most commonly produced via steam reforming

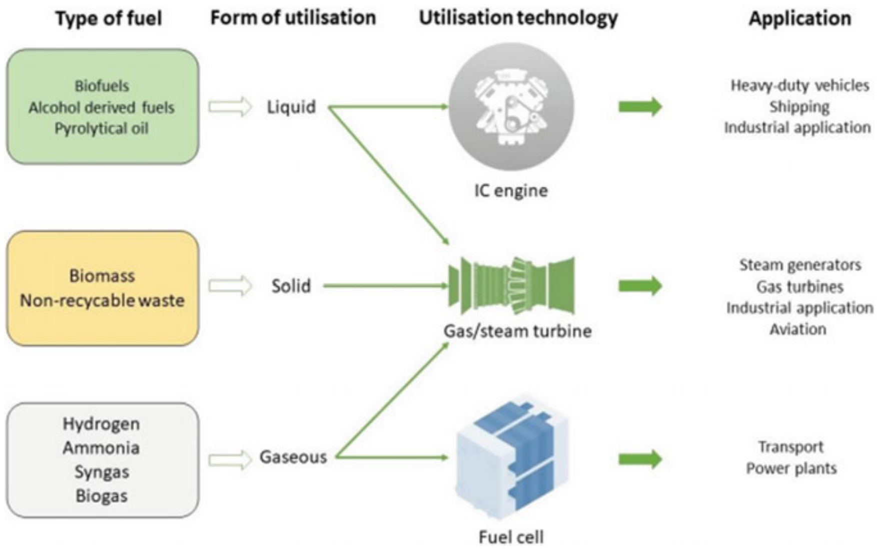


**Fig. 8.4** Technology utilization perspectives for alternative fuels. Reprinted from Stančin et al. (2020) with copyright permission obtained from Elsevier

of $CH_4$, but it can also be produced through partial or autothermal oxidation or gasification (Salazar and Kaiser 2011). Nonetheless, production from fossil fuels will be impossible in a future decarbonized energy system, hence, progressive efforts must shift towards sustainable solutions. Biomass pyrolysis or gasification is required for its production using renewable energy sources (Glaude et al. 2010). Moreover, $H_2$ can be produced directly through solar, nuclear, or industrial waste heat utilization since higher temperatures are required if hydrogen is produced directly from solar energy, because hydrogen production from concentrated solar power (CSP) appears to be the best solution (Baldwin 2008). Nuclear energy production necessitates the incorporation of waste heat for high-temperature electrolysis, which necessitates additional research (Boisen 2008). Blending $H_2$ with natural gas is a major breakthrough and a promising mixture fuel for CI engines, hence, it is suggested that higher percentages can be blended with natural gas with compositions lighter than those of diesel engines as test-fuel mixtures for ICEs.

#### 8.5.1.2 Methanol Synthesis

The use of light to drive or assist chemical reactions and processes to produce clean methanol is an innovative technology that is becoming more visible in the scientific literature (Manoharan et al. 2019). The prospect of synthesizing methanol using solar energy, $CO_2$, and water could lead to an economically viable technology capable of replacing fossil fuel with a renewable alternative (Das et al. 2020). There are several methods for producing light-assisted chemical products, including direct conversion of carbon dioxide and $H_2O$ via photochemistry, photo-electrochemistry or solar thermochemistry. Another alternative possible explanation is to gasify biomass with the aim of producing hydrogen and syngas (Glaude et al. 2010). Solar concentrators increase the amount of sunlight that strikes the biomass gasifier. The temperatures reached should be high enough (850 °C) to impact biomass gasification without additional heating (Wallner et al. 2009). The methanol produced via this technology can be made available for blending biofuels for use in ICEs.

#### 8.5.1.3 Biomethane from Anaerobic Digestion (AD)

AD is a 4-step bio-metabolism process that converts wastes which are biodegradable into valuable biogas, primarily $CH_4$ (Lee et al. 2001). The AD process is ideal for treating a biodegradable fraction of MSW, agricultural waste (harvest remains, energy crops, algal biomass, animal manures), food industry waste (starch, beverage processing, dairy), or sludge from sewage (Wallner et al. 2009). The four-step process can be applied to single-stage or multi-stage AD systems, with the last step necessitating additional modifications. Complex relationships between various operating parameters, growth factors, system design, and reactor type determine the overall process efficiency (Verhelst 2014). The feedstock type is critical for the selection of system design and reactor type, as well as for growth factors and operational parameters (Hänggi et al. 2019). During the process, pH is strictly controlled because it affects the efficiency of the bacteria and, as a result, the process's success rate. Nowadays, the majority of AD systems operate in a continuous single-stage mode while processing a variety of biodegradable waste (Salazar and Kaiser 2011). The biomethane produced can be used to atomize biodiesel such that the hybrid-fuel exhibits enhanced spray characteristics when used in ICEs.

### *8.5.2 Current Challenges and Future Trends*

Presently, there are several limitations for the efficient use of alternative fuels. First, fossil fuel availability makes it very difficult for alternative fuels to meet cost-competitive production costs (Glaude et al. 2010). Considering waste fuel and biofuels, attaining standard quality is the main concern. Also, thermal stability, higher acidity, lower heating value, and similar limits, provide wider deployment of current commercially available biofuels. However, in this field, research is still ongoing with the constant improvement on the fuels produced, indicating that the role of these fuels is not uncertain in the future (Salazar and Kaiser 2011). Alternatively, ammonia, alcohols, and hydrogen derived fuels have familiar production procedures, which are mostly synthesized for industrial use, thus indicating that higher costs of production are not a concern for such processes, however, further reduction is to be expected if the purpose is for it to be used as fuel. Additionally, the use of new fuels involves modification on the existing technologies (Wellinger and Lindberg 2000). The effective use of alcohol and biofuel in ICEs is very much possible with little or improved engine modifications of the existing ICEs, however, in the case of $H_2$ and $NH_3$ significant modification or possibly development of new technology is often required (Bordelanne et al. 2011). The development of fuel cells, for the utilization of $H_2$, demonstrates exceptional perspective to be deployed of both portable and stationary applications, even if further modifications are expected to increase efficiency as well as optimize the operating conditions. Lastly, another challenge of alternative fuels is in the production process, which is expected to shift towards sustainable and clean solutions (Salazar et al. 2009). In biofuels, for example, this implies the utilization of industrial biomass residues and agricultural wastes that will yield high-quality clean fuels. Concurrently, in achieving carbon neutrality, synthetic fuel production should tend towards new solutions that do not require the use of fossil fuels as precursor/feedstock.

Direct utilization of solar energy for fuel synthesis is a trending research, which is still ongoing. One advantage of this process is that it does not require an external source of energy (Antunes et al. 2008). Nonetheless, the low conversion efficiency of this type of energy is influenced by some factors such as overall process efficiency, thus making solar production unprofitable and cost effective. Furthermore, efforts are being made by researchers to bring innovative technologies that can be operated in flexible mode especially on a larger scale (Scarcelli et al. 2011). This is important for carbon capture and electrolysis technologies which are used to produce feedstock (hydrogen and carbon dioxide) for alternative fuel synthesis. Concerted efforts are being made by researchers to bring about thermochemical conversion methods for alternative fuel production on a larger scale basis (You et al. 2020). Gasification and pyrolysis are very important processes since they can process varieties of waste materials, thus converting them into chemicals and/or fuels. Currently, research focus is shifted to enhancing the properties of biofuels through co-gasification or co-pyrolysis with high calorific waste materials which will also help in waste management (Yadvika et al. 2004).

## 8.6 Conclusion

Dual fuel systems are promising fuels which hold future prospects as transport fuels in ICEs since a considerable number of options exist with respect to CI engines. The importance of dual fuel can be ascribed to improving thermal efficiencies, and combustion properties with reduced emissions when compared to fossil fuel. Some dual fuel types were discussed in this book which include; biogas-biomethane blends, biomethane-CNG hybrid fuels, among others. The performance, emission and combustion characteristics of dual fuels were discussed as well as other properties which could affects the fuel quality such as air -fuel ratio, power and fuel consumption, effect of dual fuel on engines lifespan and the effects of diluents on the fuel. Based on reports, it is clear that besides the use of NG and alcohol blends as fuels for ICEs, other fuel options explored for CI engines including fractions comprising of far lower ratios of biofuels relative to gasoline can be considered as these will render the fuels as light as gasoline without clearly altering the properties of gasoline such that they are fit for application in such ICEs. There is needs to install a simple gas-fuel adaptor with toughened valves and valve seats which slightly modifies the fuel adaptor in the regular engine configuration for SI engines. Furthermore, with the recent prospects of hydrogen as transport fuel, issues related to sustainable production and storage are currently being overcome which then increases the chances of the fuel becoming a replacement/an alternative fuel for gasoline such that hybrid cars that can run on either hydrogen/NG and gasoline are designed for use as modern-day vehicles. With the current advancement in today's research, there is an inkling that the road to the envisaged future of hybrid gasoline-based cars running on hydrogen/NG and NG will soon become a reality.

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