

Energy, Environment, and Sustainability

Akhilendra P. Singh
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Prospects of Alternative Transportation Fuels



 Springer

Energy, Environment, and Sustainability

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Preface

Energy demand has been rising remarkably due to increasing population and urbanization. Global economy and society are significantly dependent on the energy availability because it touches every facet of human life and its activities. Transportation and power generation are major examples of energy. Without the transportation by millions of personalized and mass transport vehicles and availability of 24×7 power, human civilization would not have reached contemporary living standards.

The first international conference on ‘Sustainable Energy and Environmental Challenges’ (SEEC-2017) was organized under the auspices of ‘International Society for Energy and Environmental Sustainability’ (ISEES) by the ‘Center of Innovative and Applied Bioprocessing’ (CIAB), Mohali, from 26 to 28 February 2017. ISEES was founded at IIT Kanpur in January 2014 with the aim of spreading knowledge in the fields of energy, environment, sustainability and combustion. The society’s goal is to contribute to the development of clean, affordable and secure energy resources and a sustainable environment for the society and to spread knowledge in the above-mentioned areas and spread awareness about the environmental challenges, which the world is facing today. ISEES is involved in various activities such as conducting workshops, seminars, conferences in the domains of its interest. The society also recognizes the outstanding works done by the young scientists and engineers for their contributions in these fields by conferring them awards under various categories.

This conference provided a platform for discussions between eminent scientists and engineers from various countries including India, USA, South Korea, Norway, Malaysia and Australia. In this conference, eminent speakers from all over the world presented their views related to different aspects of energy, combustion, emissions and alternative energy resources for sustainable development and cleaner environment. The conference started with four mini-symposiums on very topical themes, which included (i) New Fuels and Advanced Engine Combustion, (ii) Sustainable Energy, (iii) Experimental and Numerical Combustion and (iv) Environmental Remediation and Railroad Transport. The conference had 14 technical sessions on topics related to energy and environmental sustainability and a

panel discussion on ‘Challenges, Opportunities and Directions of Technical Education & Research in the Area of Energy, Environment and Sustainability’ to wrap up the three-day technical extravaganza. The conference included 2 plenary talks, 12 keynote talks, 42 invited talks from prominent scientists, 49 contributed talks and 120 posters. A total of 234 participants and speakers attended this three-day conference, which hosted Dr. V. K. Saraswat, Member NITI Aayog, India, as a chief guest for the award ceremony of ISEES. This conference laid out the road map for technology development, opportunities and challenges in this technology domain. The technical sessions in the conference included Advances in IC Engines and Fuels; Conversion of Biomass to Biofuels; Combustion Processes; Renewable Energy: Prospects and Technologies; Waste to Wealth—Chemicals and Fuels; Energy Conversion Systems; Numerical Simulation of Combustion Processes; Alternate Fuels for IC Engines; Sprays and Heterogeneous Combustion of Coal/Biomass; Biomass Conversion to Fuels and Chemicals—Thermochemical Processes; Utilization of Biofuels and Environmental Protection and Health. All these topics are very relevant for the country and the world in the present context. The society is grateful to Prof. Ashok Pandey for organizing and hosting this conference, which led to the germination of this series of monographs, which included 16 books related to different aspects of energy, environment and sustainability. This is the first time that such a voluminous and high-quality outcome has been achieved by any society in India from one conference.

The editors would like to express their sincere gratitude to the authors for submitting their work in a timely manner and revising it appropriately at short notice. We would like express to our special thanks to Prof. V. Ganeshan, Prof. P. A. Laxminarayana, Prof. D. V. Patil, Dr. Joonsik Hwang and Mr. Tanmay Kar, who reviewed various chapters of this monograph and provided their valuable suggestions to improve the manuscripts. We acknowledge the support received from various funding agencies and organizations for the successful conduct of the first ISEES conference SEEC-2017, where these monographs germinated. These include Department of Science and Technology, Government of India (special thanks to Dr. Sanjay Bajpai); TSI, India (special thanks to Dr. Deepak Sharma); Tesscorn, India (special thanks to Sh. Satyanarayana); AVL India; Horiba, India; Springer (special thanks to Swati Mehersh); CIAB (special thanks to Dr. Sangwan).

At this stage of technology development, transportation and power generation systems are dependent on conventional fuels such as mineral diesel, gasoline, which resulted in rapid depletion of petroleum reserves. Application of different alternative fuels such as biofuels, renewable fuels, alcohols and other synthetic fuels needs to be explored for sustainable development of automotive sector. This monograph is intended for practitioners working in the energy sector, and we hope that the book would be of great interest to the professionals and postgraduate students involved in

fuels, IC engines and environmental research. The main objective of this monograph is to present the status of energy sector, potential alternative fuels and the technologies for promoting the production and utilization of these alternative fuels.

Kanpur, India
Kanpur, India
Kanpur, India
Mandi, India
Dehradun, India

Akhilendra P. Singh
Rashmi Avinash Agarwal
Avinash Kumar Agarwal
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Contents

Part I General

- 1 Introduction of Alternative Fuels** 3
Akhilendra P. Singh, Avinash Kumar Agarwal,
Rashmi Avinash Agarwal, Atul Dhar and Mritunjay Kumar Shukla
- 2 Evolving Energy Scenario: Role and Scope for Alternative Fuels
in Transport Sector** 7
Akhilendra P. Singh, Atul Dhar and Avinash Kumar Agarwal

Part II Gaseous Alternative Fuels: Production and Utilization

- 3 Hydrogen Production Through Biological Route** 23
Sanjukta Subudhi
- 4 Hydrogen for Internal Combustion Engines** 39
Anuj Pal and Avinash Kumar Agarwal
- 5 Advances in Hydrogen-Fuelled Compression Ignition Engine** 55
Priybrat Sharma and Atul Dhar
- 6 Compressed Natural Gas and Hythane for On-road Passenger
and Commercial Vehicles** 79
Tadveer Singh Hora and Avinash Kumar Agarwal

Part III Biofuels

- 7 Alcohols for Fueling Internal Combustion Engines** 109
Dev Prakash Satsangi, Nachiketa Tiwari and Avinash Kumar Agarwal
- 8 Different Feedstocks and Processes for Production of Methanol
and DME as Alternate Transport Fuels** 131
Piyali Das and Anubhuti Bhatnagar

9	Solar Assisted Biodiesel Production	167
	Amit Pal, Amrik Singh and R. S. Mishra	

Part IV Advanced Techniques of Alternative Fuels

10	Fuel from Waste: A Review on Scientific Solution for Waste Management and Environment Conservation	205
	Arvind Kumar Bhatt, Ravi Kant Bhatia, Sumita Thakur, Nidhi Rana, Vaishali Sharma and Ranju Kumari Rathour	
11	Thermochemical Conversion of Biomass to Bioenergy: A Review	235
	Krishnendu Kundu, Ayoma Chatterjee, Tamashree Bhattacharyya, Madhuka Roy and Ajit Kaur	
12	Pyrolysis Oil Upgrading to Fuels by Catalytic Cracking: A Refinery Perspective	269
	Desavath Viswanatha Naik, Vimal Kumar and Basheshwar Prasad	

Part V Utilization of Alternative Fuels

13	Water-in-Diesel Nanoemulsion Fuels for Diesel Engine: Combustion Properties and Emission Characteristics	299
	Hemant Kumar, M. K. Shukla and Vimal Kumar	
14	Peroxy-fuels: Burning Behavior and Potential Applications in Combustion Engines	343
	Kirti Bhushan Mishra and Klaus-Dieter Wehrstedt	
15	Utilization of Alternative Fuels in Advanced Combustion Technologies	359
	Akhilendra P. Singh and Avinash Kumar Agarwal	
16	Fuel Injection Equipment (FIE) Design for the New-Generation Alternative Fuel-Powered Diesel Engines	387
	Gaurav Tripathi, Sarthak Nag, Atul Dhar and Dhiraj V. Patil	

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Prof. Avinash Kumar Agarwal joined IIT Kanpur in 2001 and is currently a Poonam and Prabhu Goyal Endowed Chair Professor. He was at ERC, University of Wisconsin, Madison, USA, as Postdoctoral Fellow (1999–2001). His areas of interest are IC engines, combustion, alternative fuels, hydrogen, conventional fuels, lubricating oil tribology, optical diagnostics, laser ignition, HCCI, emission and particulate control and large bore engines. He has published more than 160 peer-reviewed international journal and conference papers. He is Associate Editor of ASME Journal of Energy Resources Technology and International Journal of Vehicle Systems Modelling and Testing. He has edited 'Handbook of Combustion' (5 volumes; 3168 pages), published by Wiley VCH, Germany. He was a Fellow of SAE (2012), Fellow of ASME (2013) and a Fellow of INAE (2015). He is the recipient of several prestigious awards such as NASI-Reliance Industries Platinum Jubilee Award-2012; INAE Silver Jubilee Young Engineer Award-2012; Dr. C.V. Raman Young Teachers Award-2011; SAE International's Ralph R. Teeter Educational Award-2008; INSA Young Scientist Award-2007; UICT Young Scientist Award-2007; INAE Young Engineer Award-2005. He is the recipient of Prestigious Shanti Swarup Bhatnagar Award-2016 in Engineering Sciences. He is the first combustion/IC Engine researcher to get this honour.



Dr. Atul Dhar is Assistant Professor at IIT Mandi since 2013. He received his M.Tech. and Ph.D. degrees from Department of Mechanical Engineering, IIT Kanpur, in 2006 and 2013, respectively. He graduated from HBTI, Kanpur, in 2004. He was awarded the Erasmus Mundus fellowship of European Union for pursuing postdoctoral research at Ecole Centrale de Nantes, France, in 2013. He is the recipient of Young Scientist Award from ISEES in 2015. His areas of interest include reciprocating IC engines, emission control, alternative fuels and lubricating oil tribology. He has co-authored more than 30 international peer-reviewed journal papers.



Mr. Mritunjay Kumar Shukla graduated from Institute of Engineering and Technology, C.S.J.M. University, Kanpur, in 2003. He worked in Joined Engine Research Laboratory of IIT Kanpur from 2003 to 2006 as a Project Associate on various projects related to biogas, biodiesel, emulsified fuels, EGR and automotive coatings. In December 2006, he joined IIP, Dehradun, as Scientist B. Since then he has been working on aspects of next-generation biofuels like bio-butanol, diethyl ethers, straight vegetable oils. He is the member of Internal Combustion Engines Subcommittee, TED 2:1, and Automotive Braking Systems, Vehicle Testing and Performance Evaluation Sectional Committee, TED 4 of Bureau of Indian Standards. He also represents IIP as alternative members in Standing Committee on Emission Legislations of MoRTH. His areas of research interest include combustion emission and spray characteristics of alcohol fuels, automotive exhaust treatment devices, emulsified fuels.

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Part I
General

Chapter 1

Introduction of Alternative Fuels

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

Abstract Energy is a basic requirement for economic development. Growing energy consumption has resulted in world becoming increasingly dependent on fossil fuels such as coal, oil and gas; therefore, it becomes necessary to develop a sustainable path of energy. Gaseous fuels and biofuels seem to have the potential to contribute significantly to India's energy security. This monograph shows the current status of different alternative fuels and describes some advanced techniques to improve the quality of alternative fuels. Utilization of these alternative fuels in existing vehicles is another important aspect, which has been covered in this monograph.

Keywords Hydrogen · Biodiesel · Emission · Alcohols · Biomass

Fossil fuels supply more than 80% energy for global consumption and more than 95% energy for transport sector globally. While global fossil fuel reserves are diminishing, worldwide energy demand is constantly increasing due to the evolution of energy intensive lifestyles. To improve the security of the energy supply and to reduce the emissions of greenhouse gases (GHG), it becomes very important to explore alternative fuels for transport sector. US Department of Energy (DoE) has defined the important requirements of transportation fuel as they should be compatible with economic, environmental and societal aspects (Tzimas et al. 2004). Before selecting any alternative fuel, it is important to evaluate its economic and environmental impacts, societal needs, personal beliefs and changes to the quality of life. One chapter of this monograph presents the status of current energy scenario

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and shows the potential options as alternative fuels for automotive applications. Based on this introductory chapter, this monograph is divided into five parts.

Gaseous fuels seem a potential solution for energy supply to automotive sector in near future. These gaseous fuels contain more hydrogen and less carbon; therefore, the emission of greenhouse gases and fine particulates is lower from these fuels. Compressed natural gas (CNG)/liquefied petroleum gas (LPG)/liquefied natural gas (LNG) does not contain poly-aromatic hydrocarbons (PAHs), airborne toxins and sulphur dioxide (SO_2), and CNG/LPG/LNG vehicles have quieter engine operation, less vibrations and odour than conventional diesel engines. However, higher vehicle cost, shorter driving range, heavier fuel tank, expensive distribution and storage network and potential performance and operational problems compared to liquid fuels are some of the drawbacks of using CNG/LPG/LNG vehicles. The second part of this monograph contains few chapters based on production and utilization aspects of these gaseous fuels. One chapter based on hydrogen production from biological routes highlights in prospects and limitations of biohydrogen production including recent developments on this domain and describes the economic feasibility of biohydrogen production. This chapter also emphasizes the importance of integration of conventional hydrogen production technologies with production of value-added bio-based products in a biorefinery approach. Two chapters on hydrogen utilization in internal combustion (IC) engines explain the difficulties involved with use of hydrogen in real engines. These chapters also describe different techniques, which can be used for safe and efficient use of hydrogen in production grade engines. Last chapter of this part is based on utilization of CNG and hydrogen blends in engines, which is a potential solution to issues associated with hydrogen.

As biofuels have emerged as a potential alternative fuel to penetrate the transport sector, utilization of biofuels does not require significant changes in the infrastructure as well as in existing vehicles. There are variety of biofuels utilized in vehicles in which biodiesel and alcohols are the important ones. The production of these biofuels currently relies on proven technologies, characterized however by high costs. The third part of this monograph has three chapters on biofuels, which include status, production and utilization aspects. First chapter of this part gives the overview about different alcohols and presents the feasibility of alcohols' utilization as a replacement of mineral diesel. One chapter in this part shows the potential of methanol and di-methyl ether (DME) as alternative fuel in engine applications. This chapter also describes the chemistry and the sustainability of different pathways for their production from different feedstock such as coal, petcoke, natural gas, biomass and carbon dioxide. Last chapter of this part presents the methodology for utilization of solar energy in biodiesel production, which will certainly eliminate the carbon dioxide (CO_2) formation involved with current biodiesel preparation techniques.

Apart from exploring new alternative fuels, it is also very important to improve the conventional technologies to enhance the properties of alternative as well as conventional petroleum fuels. Fourth part of this monograph is based on such advanced technologies so that alternative fuels can be produced economically. One

chapter of this section is based on the various aspects of waste utilization in production of clean energy, which is essential for sustainable development of society and needs immediate attention. Conversion of lignocellulosic biomass feedstock into bioenergy is another interesting chapter in this part. This chapter shows that variations in composition of biomass at optimized process flow affect the quality and quantity of potential product yields. Pyrolysis oil as an attractive option for the conversion of lignocellulosic biomass into liquid alternative fuels is also included in this part of the monograph.

Utilization of these alternative fuels is the most important aspect related to sustainability of these alternative fuels. Last part of this monograph discusses the different techniques for utilization of these alternative fuels in IC engines efficiently. One chapter of this part explains the advancement and opportunities in W/D nano-emulsion fuel preparation using different surfactants and additives, which provides improved engine performance and emission characteristics. Use of peroxy-fuels in IC engines is another important aspect covered in this section. In the last two chapters, use of alternative fuels in advanced combustion technologies such as low-temperature combustion (LTC), reactivity controlled compression ignition (RCCI) and in advanced engine technologies has been explained.

This research monograph presents both fundamental science and applied innovations on several key and emerging technologies involving fossil and alternate fuel utilization in power and transport sectors. Specific topics covered in the manuscript include:

- Introduction to Alternative Fuels
- Evolving Energy Scenario and Role and Scope for Alternative Fuels in Transport Sector
- Hydrogen Production Through Biological Route
- Hydrogen for Internal Combustion Engines
- Advances in Hydrogen-Fuelled Compression Ignition Engine
- Compressed Natural Gas and Hythane for On-Road Passenger and Commercial Vehicles
- Alcohols for Fuelling Internal Combustion Engines
- Different Feedstocks and Processes for Production of Methanol and DME as Alternate Transport Fuels
- Solar Assisted Biodiesel Production
- Fuel from Waste: A Review on Scientific Solution for Waste Management and Environment Conservation
- Thermochemical Conversions of Biomass to Bioenergy: A Review
- Pyrolysis Oil Upgrading to Fuels by Catalytic Cracking: A Refinery Perspective
- Water-in-Diesel Nano-Emulsion Fuels for Diesel Engine: Combustion Properties and Emission Characteristics
- Peroxy-Fuels: Burning Behaviour and Potential Applications in Combustion Engines

- Utilization of Alternative Fuels in Advanced Combustion Technologies
- Fuel Injection Equipment (FIE) Design for the New-Generation Alternative-Fuel Powered Diesel Engines

The topics are organized into five different sections: (i) General, (ii) Gaseous Alternative Fuels: Production and Utilization, (iii) Biofuels, (iv) Advanced Techniques for production of Alternative Fuels and (v) Utilization of Alternative Fuels.

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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 $\sim 95\%$ energy for the transport sector (Fig. 2.1). Figure 2.1 shows that $\sim 95\%$ 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

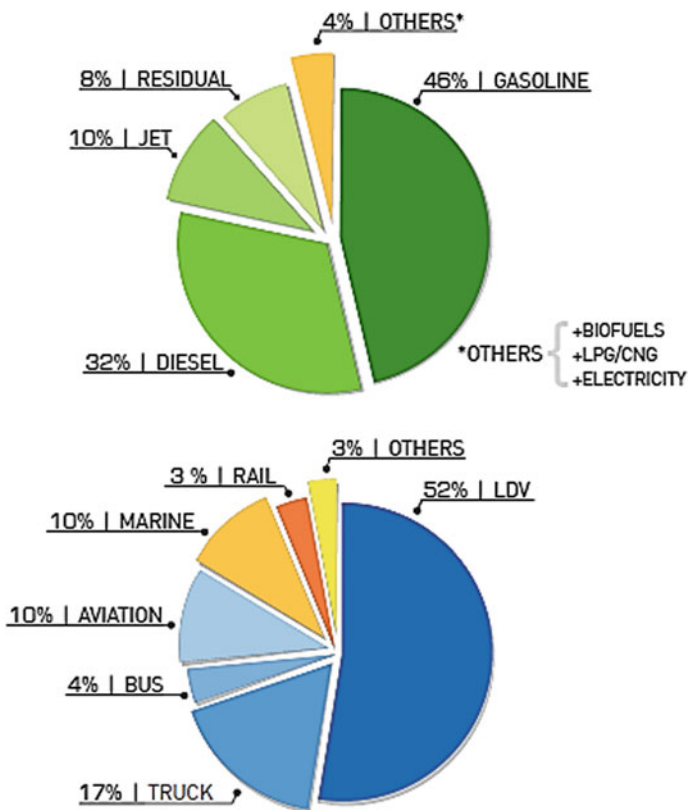


Fig. 2.1 Current global transport energy sources and consumption trends (2011) (World Economic Forum et al. 2011)

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 $\sim 95\%$ 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 (NO_x), 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

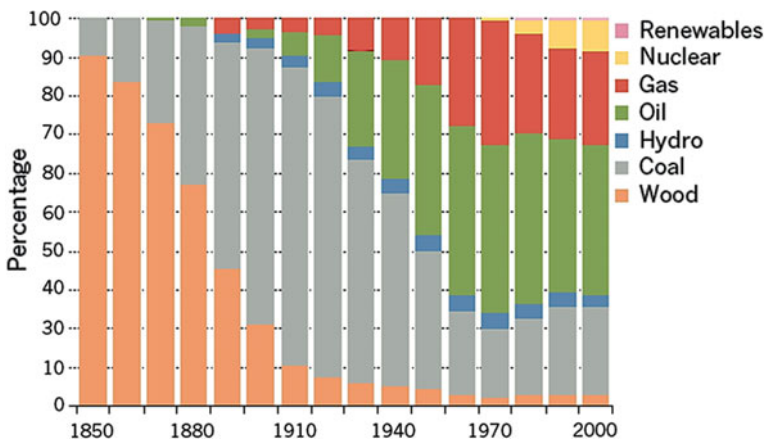


Fig. 2.2 History of relative mix of main energy resource used in the USA (Energy Information Administration. Annual Energy Review 2010)

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 CO₂ 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 NO_x emissions while producing almost similar engine torque output (Agarwal 2007; Balki et al. 2012).

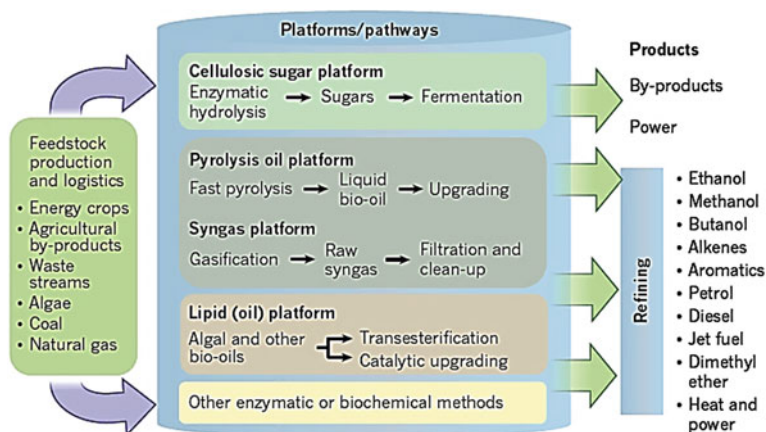


Fig. 2.3 Methods of producing alternative fuels from various biomass feedstocks to products (US Department of Energy 2011)

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 NO_x 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