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Effect on the performance and emissions of an industrial diesel engine operated on dual-fuel mode using hydrogen as secondary fuel

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Dedication

No word, no expression will be able to explain my love, my gratitude towards those who guided and encouraged me, by their abundant sacrifices, by their unconditional support engraved with the funds of my heart and spirit, towards those who have make me what I became today

My dear mother, thank you for your great love and your sacrifices. God gives you a long life

To my brothers Mohammed Moussa & Nadir and my sister, for their encouragement

All my friends: Soumia, Sara, Aicha, Salah, Belkhir and Adel

To all those who are dear to me.

I dedicate this work to them.

Redouani Wafa.

Dedication

My special gratitude goes to my parents who leads me through the valley of darkness with light of hope and support. "Dino" who stands by me when things look bleak. My beloved sisters and brother "Manel, Maria and Imad" for their support, encouragement and patience. My friends "Kahina, Soumia and Imen" for encouraging me to press on when I most wanted to quit. They provided me throughout my entire life and particularly through the process of pursuing the master degree.

I dedicate this work to all those who believed in me and pried for my success.

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Table of contents

Page

Nomenclature I

List of figures III

List of tables V

General introduction 1

Chapter I : Diesel engine description

1. Introduction 3

2. History of diesel engine 3

3. Diesel engine principle 4

4. Thermodynamic cycle 4

4.1. Spark ignition engines 4

4.2. Compression ignition engines 5

5. Internal combustion engines (ICE) operating cycles 6

5.1. Four-stroke engine cycle 6

5.2. Two-stroke engine cycle 7

6. Diesel combustion systems 8

6.1. Direct-injection engines 8

6.2. Indirect-injection engines 8

7. Major components of a diesel engine 9

7.1. Engine cylinder block 9

7.2. Crankcase and oil pan 10

7.3. Cylinder sleeve or bore 10

7.4. Piston and piston rings 11

8. Diesel engine support systems 15

8.1. Engine cooling 15

8.2. Engine lubrication 15

8.3. Fuel system 16

8.4. Air intake system 17

8.5. Exhaust System 18

9. Conclusion 19

Chapter II : Hydrogen as an alternative fuel

1. Introduction 20
2. Renewable hydrogen as an alternative fuel 20
2.1. Renewable hydrogen 20
2.2. Hydrogen discovery 20
2.3. Hydrogen properties 21
2.4. Hydrogen production from renewable energy resources 22
2.4.1. Electrolytic hydrogen production 23
2.4.2. Hydrogen production from biomass 24
2.4.3. Thermo-chemical water splitting 25
3. Hydrogen storage 25
4. Hydrogen use 26
4.1. Hydrogen as Fuel Cells 27
4.2. Hydrogen as an electric bridge 27
5. Dual fuel 27
5.1. Dual fuel working principal 27
5.2. Dual fuel injection system 28
5.2.1 Hydrogen direct injection technique 28
5.2.2 Hydrogen indirect injection technique 28
5.2.3 Central injection or carbureted system 29
6. Review of experimental and theatrical investigations of other alternative fuels 29
6.1. Natural gas 30
6.2. Biodiesel 30
6.3. Liquefied petroleum gas 31
7. Conclusion 32

Chapter III : Effect of hydrogen-diesel performance on a dual-fuel engine

1. Introduction 33
2. Engine description 33
3. Performance evaluation of engine 34
3.1. Stoichiometric air quantity 35
3.1.1. Diesel combustion 35
3.1.2. Hydrogen combustion 35
3.2. Hydrogen as an energy carrier 37
3.3. Fuel substitution 37
3.4. Specific fuel consumption of a cat 3512 engine 39
4. Effect of dual fuel operation on emissions 40

4.1. Hydrocarbons emission 41
4.2. Carbon monoxide emission 41
4.3. Carbone dioxide emission 42
4.4. Oxides of nitrogen emission 43
5. Comparative analysis 44
5.1. Comparative performance analysis 44
5.2. Comparative emission analysis 45
6. Technical-economic analysis 47
6.1 Technical analysis 47
6.1.1 Site selection 47
6.1.2 System description 48
6.1.3. Installation dimensioning (REn / H2) 49
6.1.3.1. Energy dimensioning of the electrolyser 49
6.1.3.2. Dimensioning of photovoltaic production 50
6.2 Economic study 51
6.2.1 Total investment cost 52
6.2.1.1. Initial investment (I_0) 52
6.2.1.2. Operation and maintenance costs 52
6.2.2. Levelized Cost of Electricity (LCOE) 52
7. Conclusion 54
General conclusion 55
References 57
Annexes 62
Annex I 62

Effect on the performance and emissions of an industrial diesel engine operated on dual-fuel mode using hydrogen as secondary fuel

Abstract

For environmental awareness, the increasing demand of fossil fuels and the high price of conventional fuels are urgently makes us work for research to find out the viable alternative fuels for meeting sustainable energy demand with minimum environmental impact. Hydrogen is expected to be one of the most important fuels in the near future. Hydrogen can be combined with diesel to increase performance and reduce pollution emissions that can be motivate its use in a dual-fuel mode for the industrial diesel engine. The purpose of this investigation is studying the performance effect and emissions characteristics of diesel engine Caterpillar 3512 converted to dual fuel mode using hydrogen as secondary fuel, and diesel fuel as ignition source. The effect of a wide range of equivalence ratios on the specific fuel consumption and engine exhaust emissions were examined for hydrogen-diesel fuel operation and compared with pure diesel engine. These investigations applied for the drilling rigs of the National Well Engineering Company (ENTP).

Keywords: Dual-fuel mode; Industrial Diesel engine; Hydrogen; Performance; Emissions.

Effet sur les performances et les émissions d'un moteur diesel industriel fonctionnant en mode dual-fuel utilisant l'hydrogène comme combustible secondaire

Résumé

Pour la sensibilisation à l'environnement, la demande croissante de combustibles fossiles et le prix élevé des carburants conventionnels nous oblige à travailler d'urgence pour la recherche afin de trouver les carburants alternatifs viables pour répondre à la demande énergétique durable avec un impact environnemental minimum. L'hydrogène devrait être l'un des carburants les plus importants dans un proche avenir. L'hydrogène peut être combiné avec du diesel pour augmenter les performances et réduire les émissions polluantes qui peuvent motiver son utilisation dans un mode dual-fuel pour le moteur diesel industriel. Le but de cette étude est d'étudier l'effet de performance et les caractéristiques d'émissions du moteur diesel Caterpillar 3512 converti en mode biocarburant utilisant l'hydrogène comme combustible secondaire, et le carburant diesel comme source d'allumage. L'effet d'un large éventail de rapports d'équivalence sur la consommation spécifique de carburant et les émissions de gaz d'échappement des moteurs a été examiné pour le fonctionnement hydrogène-diesel et comparé au moteur diesel pur. Ces investigations ont été appliquées de l'Entreprise Nationale des Travaux aux Puits (ENTP).

Mots clés : Mode dual-fuel ; Moteur diesel industriel ; Hydrogène ; Performance ; Emissions.

التأثير على أداء وانبعاثات محرك ديزل صناعي يعمل على وضع الوقود المزدوج باستخدام الهيدروجين كوقود ثانوي

ملخص

إن الوعي البيئي، و الطلب المتزايد على الوقود الأحفوري وارتفاع أسعار الوقود التقليدي يجعلنا نعمل على وجه السرعة من أجل البحث عن أنواع الوقود البديلة الصالحة لتلبية الطلب المستدام على الطاقة بأقل تأثير بيئي. من المتوقع أن يكون الهيدروجين أحد أهم أنواع الوقود في المستقبل القريب. يمكن دمج الهيدروجين مع الديزل لزيادة الأداء وتقليل انبعاثات التلوث التي يمكن أن تحفز استخدامها في وضع الوقود المزدوج لمحرك الديزل الصناعي. الغرض من هذا التحقيق هو دراسة تأثير الأداء وخصائص الانبعاثات لمحرك الديزل Caterpillar 3512 المحول إلى وضع الوقود المزدوج باستخدام الهيدروجين كوقود ثانوي، ووقود الديزل كمصدر للإشعال. تم فحص تأثير مجموعة واسعة من نسب التكافؤ على استهلاك الوقود المحدد وانبعاثات محرك العادم من أجل تشغيل وقود الديزل الهيدروجيني ومقارنته مع محرك الديزل النقي. وقدرت هذه التحقيقات للمؤسسة الوطنية للأشغال في الابار (ENTP).

كلمات البحث: وضع الوقود المزدوج؛ محرك ديزل صناعي؛ هيدروجين؛ الأداء؛ الانبعاثات.

Nomenclature

Symbol	**Definition**	**Unit**
A	Total area of photovoltaic generator m²	m²
C	Costs	$
C_r	Replacement cost	$
deg	Degradation rate	%
E	Energy absorbed by the electrolyser	Kg/toe
EF	Emission factor	kWh
I_0	Initial investment cost	$
$K_{el,th}$	Theoretical electrolytic power consumption	kWh /
LHV	Lower heating value	kJ/kg
$\dot{m}$	Mass flow	kg/h
N	System life	years
P	Power input by Diesel or Hydrogen	kW
r	Discount rate	%
S	Fuel substitution	%
SFC	Specific Fuel Consumption	g/kWh

Greek letters

$\emptyset_T$	Total fuel-air equivalence ratio	/
η	Efficiency	%

Abbreviations

D	**D**iesel
DFM	**D**ual **F**uel **M**ode
H_2	**H**ydrogen
LPG	**L**iquefied **P**etroleum **G**as
PV	**P**hoto**v**oltaic
REn	**R**enewable **En**ergy
LCC	**L**ife **C**ycle **C**ost
LCOE	**L**evelized **C**ost **O**f **E**lectricity

Clue

a	Fuel type
el	Electrolyser
M&O	Maintenance and operating
pv	Photovoltaic
t	Thermal

List of figures

Chapter I : Diesel engine description

Fig. I.1 Example of a large skid-mounted, diesel-driven generator 4

Fig. I.2 Example of spark ignition engine 5

Fig. I.3 Example of compression ignition engine 5

Fig. I.4 Four-stroke spark-ignition ICE cycle 6

Fig. I.5 Detroit Diesel 4-71N two-stroke combustion process 7

Fig. I.6 Common types of DI engine combustion systems 8

Fig. I.7 Two common types of small indirect-injection diesel engine combustion system 9

Fig. I.8 Diesel engine cylinder block 10

Fig. I.9 Diesel engine cylinder sleeve 11

Fig. I.10 Diesel engine piston and piston rod 11

Fig. I.11 Diesel engine crankshaft and bearings 12

Fig. I.12 Diesel engine valve 13

Fig. I.13 Diesel engine camshaft and drive gear 14

Fig. I.14 Diesel engine valve train 15

Fig. I.15 Engine cooling system 16

Fig. I.16 Engine lubrication system 17

Fig. I.17 Diesel engine fuel flow path system 18

Fig. I.18 Air intake system 18

Fig. I.19 Oil bath air filter 19

Fig. I.20 Diesel engine exhaust system 20

Chapter II: Hydrogen as an alternative fuel

Fig. II.1 Sir William Grove constructed hydrogen-filled the first fuel cell in 1938 21

Fig. II.2 Alexandre Cesar Charles with his William Grove constructed hydrogen-filled balloon in 1783 21

Fig. II.3 The hydrogen atom 22

Fig. II.4 Some alternative processes for hydrogen production 22

Fig. II.5 Principle drawing of iodine/sulfur thermo-chemical process 25

Fig. II.6 Dual fuel operation 28

Fig. II.7 Hydrogen direct injection 28

Fig. II.8 Hydrogen indirect injection 29

Fig. II.9 Hydrogen central injection 29

Chapter III: Performance of a dual-fuel hydrogen-diesel engine

Fig. III.1 Description of the Caterpillar 3512 engine 34

Fig. III.2 Dual-fuel engine operation 35

Fig. III.3 Variation of SFC for different substitution ratios 39

Fig. III.4 Effect of dual fuel and engine load on hydrocarbon emission 41

Fig. III.5 Effect of dual fuel and engine load on CO emission 42

Fig. III.6 Effect of dual fuel and engine load on CO2 emission 43

Fig. III.7 Effect of dual fuel and engine load on NOx emission 44

Fig. III.8 Comparative analysis of the performance characteristics of CAT3512 45

Fig. III.9 Basic diagram of the hydrogen production plant 49

List of tables

Chapter III : Performance of a dual-fuel hydrogen-diesel engine

Tab. III.1 General specification of the Caterpillar 3512 diesel engine 34

Tab. III.2 Comparison between diesel-hydrogen properties 37

Tab. III.3 Characteristics of the Caterpillar 3512 engine operating at 80% of nominal power with different diesel / hydrogen ratios 39

Tab. III.4 Emission Factors for Fuels Diesel / Hydrogen 40

Tab. III.5 Comparison effect of dual fuel engine on CO2, CO, NOx and HC emission 45

Tab. III.6 ENTP drilling equipment park 2016 47

Tab. III.7 Global Horizontal Irradiation of Hassi Messaoud 48

Tab. III.8 Dimensioning of the industrial electrolyser of the selected alkaline technology 50

Tab. III.9 Dimensioning of photovoltaic generator 51

Tab. III.10 Characteristic of the PV used technology 53

Tab. III.11 Techno-economic electrolysis study for different capacities 54

General introduction

General introduction

Today, diesel engines have emerged as a means of energy production dominant in the world market. This is due to the substantial improvements of these engines [1]. However, global consumption of fossil fuels is increasing, and the proven reserves of fossil fuels are decreasing. In addition, awareness of the environmental consequences has grown steadily. In fact, large quantities of chemical substances are released into the environment, most of them being considered dangerous. The introduction of these compounds involves serious risks not only for the environment and living organisms, but also for human health. Behind the term of air, pollution lies a wide variety of pollutants. The sources of polluting emissions are multiple (industrial combustion gases, automobile exhaust gases, emissions from factories, etc.). The most traditional emissions are the following: carbon dioxides (CO_2), nitrogen oxides (NO and NO_2), carbon monoxides (CO) and unburned hydrocarbons (HC).

In order to eliminate these emissions and a shortage on oil production, dual fuel technology is considered as a key solution to reduce emissions. It is expected to reduce pollutant emissions under acceptable economic conditions while limiting reliance on fossil petroleum products. This technology consist of using fossil resources such as natural gas, liquefied petroleum gas (LPG) and renewable resources such as hydrogen, methanol and bioethanol. Renewable energies (REn) have the advantage of being inexhaustible regardless of consumption and being non-emitting greenhouse gas (GHG). Their operations are a way to meet energy needs while preserving the environment. The main sources of renewable energy are hydro, solar, wind, biomass and geothermal.

Renewable hydrogen is considered as a promising energy carrier in the future it has a number of advantages. It is not a pollutant and does not contaminate the ground water [2]. Several techniques exist for the production of hydrogen from renewable energy sources such as biomass and water with input from renewable energy sources [3]

For Algeria, hydrogen as an energy carrier represents a great opportunity and opens up undeniable prospects. First, it ensures a diversification and an increase in its energy resources. Then, it offers the opportunity to keep its place in the energy market. Finally, it allows it to meet its internal energy needs, which become more and more important. The amount of solar radiation in Algeria means that it would be feasible to consider solar energy as a potential energy source for different applications in the form of individual photovoltaic solar panels or systems.

The main objective of the present study is to investigate the combustion performance and emission characteristics of the Caterpillar3512 diesel engine converted into dual-fuel mode using hydrogen as an alternative fuel.

The chapter I « *Diesel engine description* » provides a general description to internal combustion engines, and an overview of the history behind the diesel engine and the man that invented it, Rudolf Diesel. It also covers the basic operating principles of diesel engines and lays its major components. We also defined the supporting systems of the diesel engine.

The chapter II « *Hydrogen as an alternative fuel* » presents the hydrogen as a renewable energy, in terms of resources, production, storage and uses. It also shows that hydrogen can be uses as a secondary fuel for a dual fuel operation. The chapter also highlighted through an extensive literature review into detail in describing of other alternative fuels and its environmental impacts

The last chapter « *Effect of hydrogen-diesel performance on a dual-fuel engine* » presents the performance effect and emission characteristics of a Caterpillar 3512 engine with a direct injection converted to dual fuel mode using different fuel ratio, Then we make a comparative analysis of the results we obtained with another work that used LPG as alternative fuel. Finally, an energy dimensioning of the hydrogen production installation. is presented. As well as the economic benefits of this dual fuel technology.

Finally, we will conclude this dissertation with a general conclusion, we will present a summary of the work we have done and the main results obtained.

Chapter I

Diesel engine description

1. Introduction

Most industrial power facilities require some type of prime mover to supply mechanical power for pumping, electrical power generation, operation of heavy equipment. Although several types of prime movers are available such as gasoline engines, steam and gas turbines, the diesel engine is the widely used throughout our society [3]. It powers trucks that deliver products to our communities, buses that carry us to school and work, agricultural equipment that plants and harvests our food, and backup generators that can provide electricity during emergencies. It is also used for many other applications.

The aim of this chapter is to introduce the fundamentals of internal combustion engine (ICE). The chapter traces the mechanism of operation of diesel engine and its different kinds based on the operation mechanism, specially the two stroke and four stroke engines. It also involves the thermodynamics cycle of these engines. The chapter highlight components of diesel engine, it continues by introducing engine-supporting systems.

2. History of diesel engine

The diesel engine, named after the German engineer Rudolf Diesel, the original cycle proposed by Rudolf Diesel in 1892 was similar to Carnot cycle (constant temperature cycle) that would require much higher compression than what is needed for compression ignition.

RODULF DIESEL has developed the first compression-ignition engine, compressing air inside the cylinder and obtaining a high enough air temperature to ignite a finely pulverized fuel. Nowadays, the progress made especially in mechanical injection and electronic injection shows that diesel engines are used more and more in the power plant industry, in boats and on road vehicles [4].

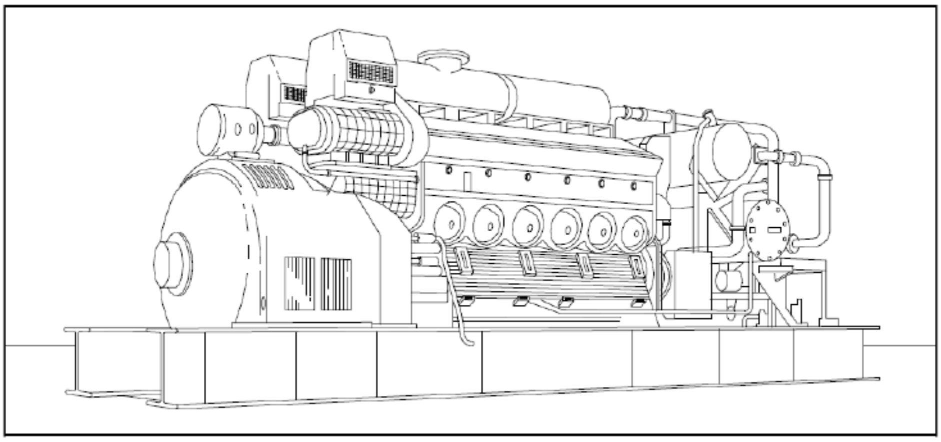

Figure I.1: Example of a large skid-mounted, diesel-driven generator [5].

3. Diesel engine principle

The diesel engine is defined as an internal combustion engine, in which ignition of the fuel, which is injected into the combustion chamber, is caused by the elevated temperature of the air in the cylinder due to mechanical compression. Diesel engines work by compressing only the air into the combustion chamber. The air is then compressed with a compression ratio. This high compression causes the temperature of the air to rise. At about the top of the compression stroke, fuel is injected directly into the compressed air in the combustion chamber. The heat of the compressed air vaporizes fuel from the surface of the droplets; then the heat from the compressed air in the combustion chamber ignites the vapor, the droplets continue to vaporize from their surfaces and burn, getting smaller, until all the fuel in the droplets has been burnt [4].

4. Thermodynamic cycle

4.1. Spark ignition engines

Spark Ignition (SI) Engine is a type of engine in which the combustion takes place by the spark generated by the spark plug. It uses petrol as fuel. In the spark ignition engine the air fuel mixture is inserted into the cylinder with help of carburetor. The compression of the fuel takes place but it has low compression ratio. The spark generated by the spark plug ignites the fuel. SI engine produces less noise and vibration and their starting is very easy. They are light in weight and have less maintenance cost. They are mostly used in light commercial vehicles such as scooters, motorcycles cars etc [6].

Figure I.2: Example of spark ignition engine [6]

4.2. Compression ignition engines

Compression Ignition (CI) engine is an engine in which the combustion of fuel takes place by the heat of the compressed air. It uses diesel as fuel. In the compressed ignition engine, only air enters into the cylinder during suction stroke. It has high compression ratio because of the high ignition temperature of the diesel fuel. The heat of the compressed air ignites the fuel. Due to high compression ratio, it produces more power. They are mostly used in heavy-duty vehicles such as buses, trucks, railways, ships etc [6].

Figure I.3: Example of compression ignition engine [6]

5. Internal combustion engines (ICE) operating cycles

Depending on the number of piston strokes required for one power cycle, internal combustion engines can be characterized as four-stroke or two-stroke. Both cycles are applicable to both spark ignition SI and compression ignition CI engines [3].

5.1. Four-stroke engine cycle

The majority of SI and CI engines operate on what is known as the four-stroke cycle. Each cylinder requires four strokes of its piston-two revolutions of the crankshaft-to complete the sequence of events, which produces one power, stroke (Figure I.4) [3]:

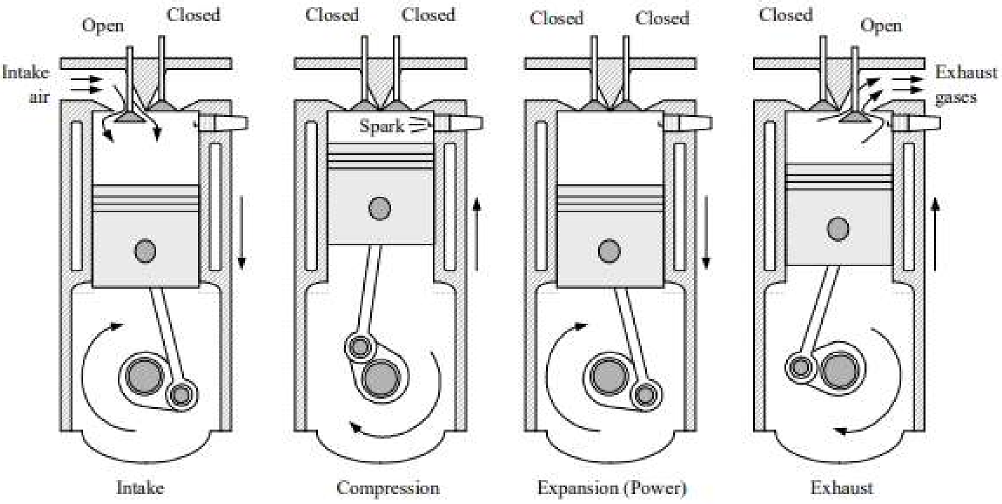

Figure I.4: Four-stroke spark-ignition ICE cycle [7].

1. An intake stroke, which draws fresh mixture into the cylinder. To increase the mass inducted, the inlet valve opens shortly before the stroke starts and closes after it ends.

2. A compression stroke, when both valves are closed and the mixture inside the cylinder is compressed to a small fraction of its initial volume. Toward the end of the compression stroke, combustion is initiated and the cylinder pressure rises more rapidly.

3. Expansion stroke, which starts with high-temperature, high-pressure, gases push the piston down and force the crank to rotate. As the piston approaches to the end of the valve, the exhaust valve opens to initiate the exhaust process and drop the cylinder pressure to close to the exhaust pressure.

4. An exhaust stroke, where the remaining burned gases exit the cylinder. Then the cycle starts again.

5.2. Two-stroke engine cycle

The two-stroke engine power cycle only requires two piston strokes, or one revolution of the crankshaft. The two-stroke cycle is applicable to both SI and CI engines [3].

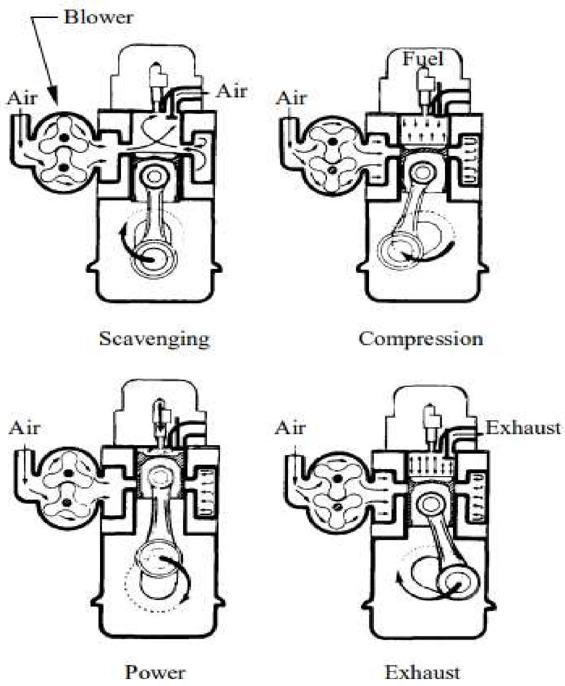

Figure I.5: Detroit Diesel 4-71N two-stroke combustion process [7].

1. A compression stroke, which starts by closing the inlet and exhaust ports, and then compresses the cylinder contents and draws fresh charge into the crankcase. As the piston approaches top-center, combustion is initiated.

2. Expansion stroke, similar to that in the four-stroke cycle until the piston approaches bottom-center, when first the exhaust ports and then the intake ports are uncovered (Figure I.5). Most of the burnt gases exit the cylinder in an exhaust blow down process. When the inlet ports are uncovered, the fresh charge, which has been compressed in the crankcase, flows into the cylinder.

6. Diesel combustion systems

Diesel engines are divided into two basic categories according to their combustion chamber design [3]:

6.1. Direct-injection engines

Direct injection (DI) diesel engines have a single open combustion chamber into which fuel is injected directly. Usually the combustion chamber shape is a shallow bowl in the crown of the piston and a central multi-hole injector is used. There are three different combustion chamber designs for direct injection diesel engines a) Quiescent chamber with multi-hole nozzle

b) Bowl-in-piston chamber with swirl and multi-hole nozzle c) Bowl-in-piston chamber with swirl and single-hole nozzle, as shown in Figure I.6.

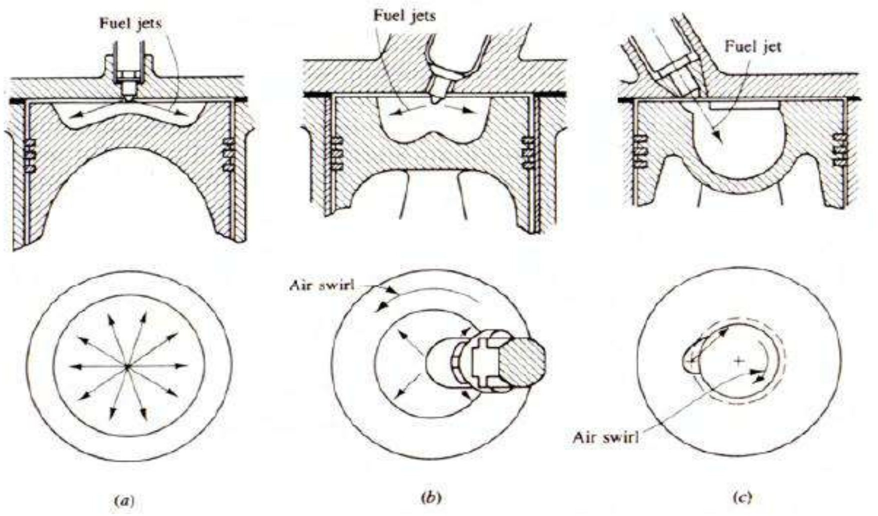

Figure I.6: Common types of DI engine combustion systems. (a) Quiescent chamber with multi-hole nozzle (b) Bowl-in-piston chamber with swirl and multi-hole nozzle (c) Bowl-in-piston chamber with swirl and single-hole nozzle [3].

6.2. Indirect-injection engines

indirect injection systems (IDI) engines , where the chamber is divided into two regions and the fuel is injected into the "pre-chamber" which is connected to the main chamber via a nozzle, or one or more orifices. IDI engine designs are only used in the smallest engine sizes.

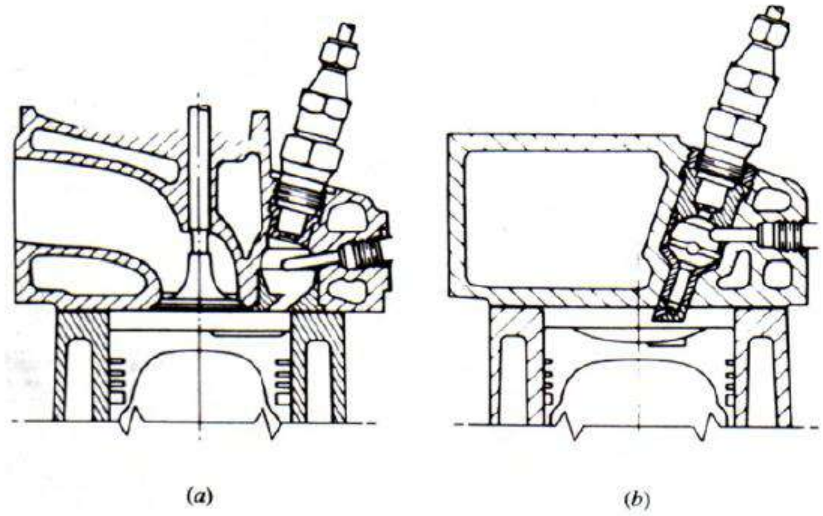

Figure I.7: Two common types of small indirect-injection diesel engine combustion system: (a) swirl pre-chamber (b) turbulent pre-chamber [3].

During compression, air is forced from the main chamber above the piston through orifice or nozzles into a pre-chamber. There are two common types of indirect-injection diesel engine systems can be defined: a) swirl pre-chamber b) turbulent pre-chamber, as shown in Figure I.7. Air can be set up to allow for adequate mixing of the air and fuel depending on the chamber shape vigorous flow or rotation (swirl).

7. Major components of a diesel engine

7.1. Engine cylinder block

The cylinder block is the main body part of the engine. As shown in Figure I.8, it is generally made as a cast iron mono-block. In a liquid-cooled diesel, the block also provides the structure and rigid frame for the engine's cylinders, water coolant and oil passages, and support for the crankshaft and camshaft bearings [5].

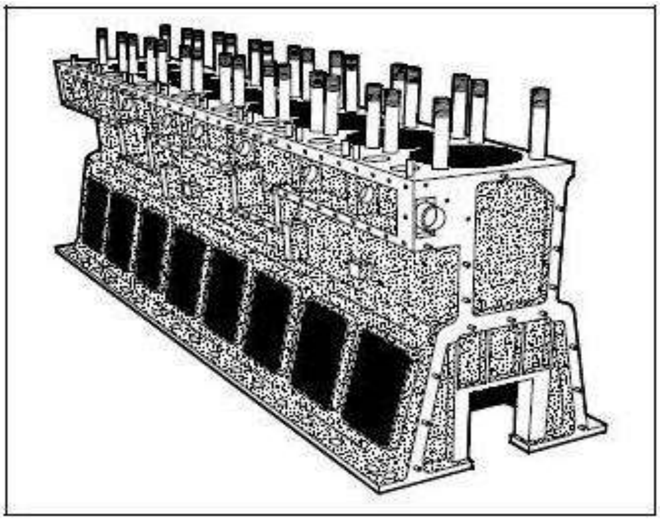

Figure I.8: Diesel engine, cylinder block [5].

7.2. Crankcase and oil pan

The crankcase is defined as the area around the crankshaft and crankshaft bearings. The crankcase is usually located on the bottom of the cylinder block. This area encloses the rotating crankshaft and crankshaft counter weights and directs returning oil into the oil pan. The oil pan is located at the bottom of the crankcase. The oil pan collects and stores the engine's supply of lubricating oil [5].

7.3. Cylinder sleeve or bore

Most diesel engines are multi-cylinder engines and typically have their cylinders arranged in one of two ways, an in-line or a "V". Diesel engines use one of two types of cylinders. In one type, each cylinder is simply machined or bored into the block casting, making the block and cylinders an integral part. In the second type, a machined steel sleeve is pressed into the block casting to form the cylinder. With either method, the cylinder sleeve or bore provides the engine with the cylindrical structure needed to confine the combustion gasses and to act as a guide for the engine's pistons [5].

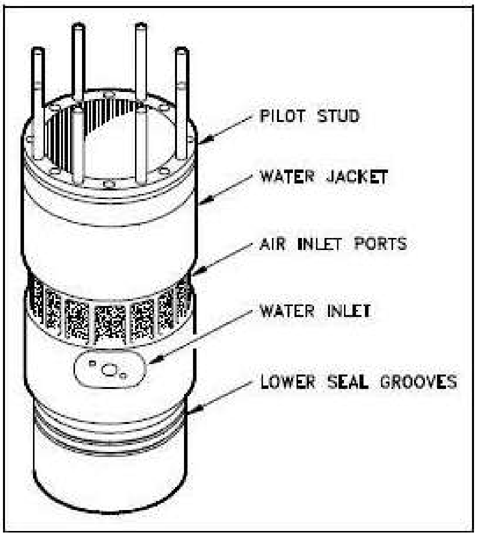

Figure I.9: Diesel engine cylinder sleeve [5].

In engines using sleeves, there are two types of sleeves, wet and dry. A dry sleeve is surrounded by the metal of the block and does not come in direct contact with the engine's coolant (water). A wet sleeve comes in direct contact with the engine's coolant. Figure I.9 provides an example of a wet sleeve. The volume enclosed by the sleeve or bore is called the combustion chamber and is the space where the fuel is burned [5].

7.4. Piston and piston rings

Pistons are commonly made of aluminum or cast iron alloys. The piston transforms the energy of the expanding gasses into mechanical energy. To prevent the combustion gasses from bypassing the piston and to keep friction to a minimum, each piston has several metal rings around it, as illustrated by Figure I.10 [5].

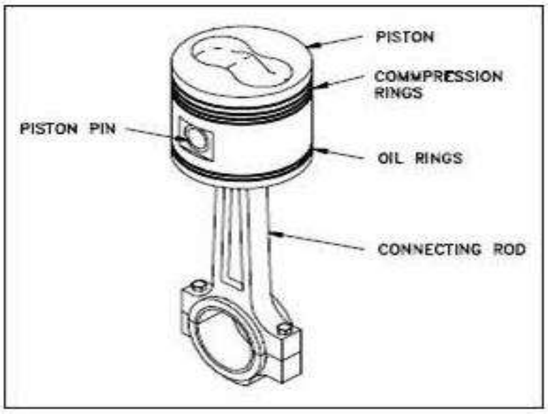

Figure I.10: Diesel engine piston and piston rod [5].

These rings function as the seal between the piston and the cylinder wall and act to reduce friction by minimizing the contact area between the piston and the cylinder wall. The top ring acts primarily as the pressure seal. The intermediate ring acts as a wiper ring to remove and control the amount of oil film on the cylinder walls. The bottom ring is an oiler ring and ensures that a supply of lubricating oil is evenly deposited on the cylinder walls [5].

1.5. Connecting rod

The rods are made from dropforged. Each end of the rod is bored, with the smaller top bore connecting to the piston pin (wrist pin) in the piston as shown in Figure I.11. The large bore end of the rod is split in half and bolted to allow the rod to be attached to the crankshaft. Some diesel engine connecting rods are drilled down the center to allow oil to travel up from the crankshaft and into the piston pin and piston for lubrication. The connecting rod connects the piston to the crankshaft [5].

7.6. Crankshaft

The crankshaft transforms the linear motion of the pistons into a rotational motion that is transmitted to the load. Crankshafts are made of forged steel. The forged crankshaft is machined to produce the crankshaft bearing and connecting rod bearing surfaces. The rod bearings are eccentric, or offset, from the center of the crankshaft as illustrated in Figure I.11. This offset converts the reciprocating (up and down) motion of the piston into the rotary motion of the crankshaft [5].

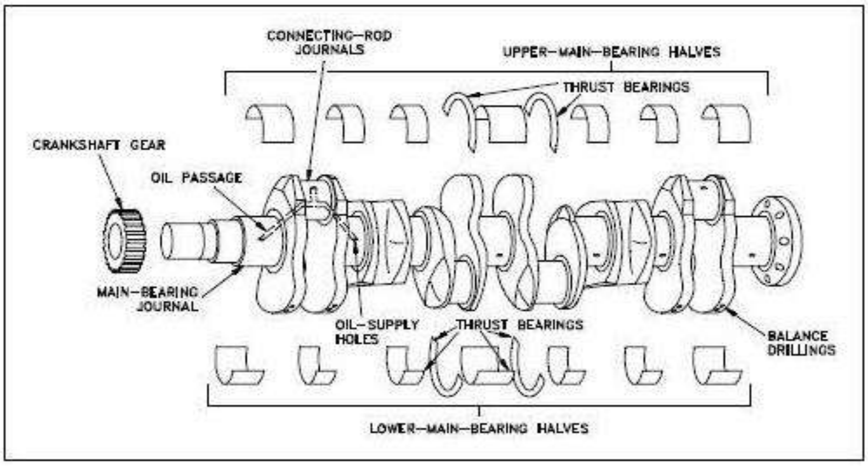

Figure I.11: Diesel engine crankshaft and bearings [5].

7.7. Flywheel

The flywheel is located on one end of the crankshaft and serves three purposes. First, through its inertia, it reduces vibration by smoothing out the power stroke as each cylinder fires. Second, it is the mounting surface used to bolt the engine up to its load. Third, on some diesels, the flywheel has gear teeth around its perimeter that allow the starting motors to engage and crank the diesel [5].

7.8. Cylinder heads and valves

A diesel engine's cylinder heads perform several functions. First, they provide the top seal for the cylinder bore or sleeve. Second, they provide the structure holding exhaust valves (and intake valves where applicable), the fuel injector, and necessary linkages. A diesel engine's heads are manufactured in one of two ways. In one method, each cylinder has its own head casting, which is bolted to the block. This method is used primarily on the larger diesel engines. In the second method, which is used on smaller engines, the engine's head is cast as one piece (multi-cylinder head). As shown in Figure I.13, valves are mechanically opened and closed to admit or exhaust the gasses as needed. The valves are located in the head casting of the engine. The point at which the valve seals against the head is called the valve seat. Most medium-sized diesels have either intake ports or exhaust valves or both intake and exhaust valves [5].

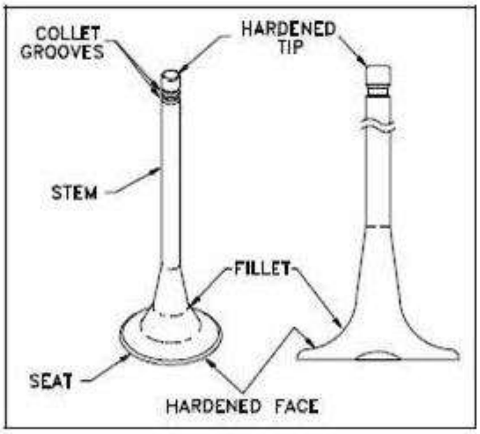

Figure I.12: Diesel engine valve [5]

7.9. Timing gears, camshaft, and valve mechanism

In order for a diesel engine to operate, all of its components must perform their functions at very precise intervals in relation to the motion of the piston. To accomplish this, a component called a camshaft is used. Figure I.13 illustrates a camshaft and camshaft drive gear [5].

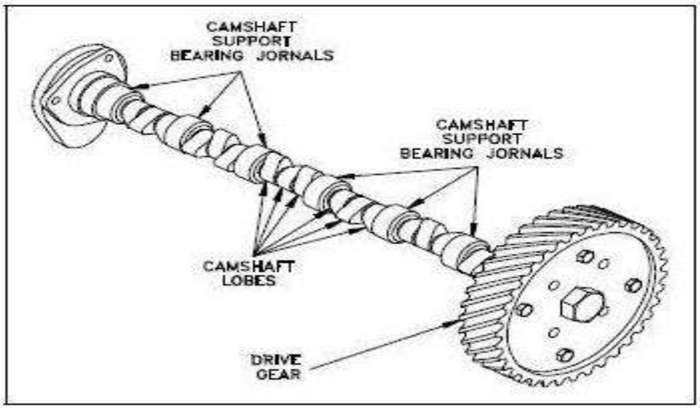

Figure I.13: Diesel engine camshaft and drive gear [5].

A camshaft is a long bar with egg-shaped eccentric lobes, one lobe for each valve and fuel injector. Each lobe has a follower as shown on Figure I.14. As the camshaft is rotated, the follower is forced up and down as it follows the profile of the cam lobe. The followers are connected to the engine's valves and fuel injectors through various types of linkages called pushrods and rocker arms. The pushrods and rocker arms transfer the reciprocating motion generated by the camshaft lobes to the valves and injectors, opening and closing them as needed [5].

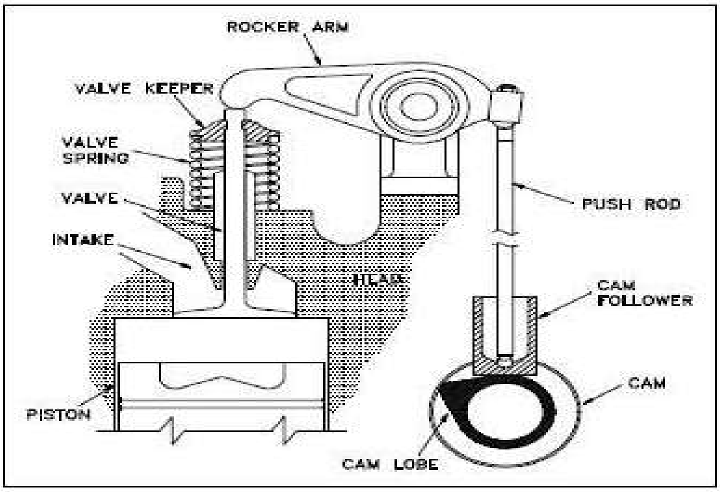

Figure I.14 : Diesel engine valve train [5].

7.10. Blower

The diesel engine blower is part of the air intake system and serves to compress the incoming fresh air for delivery to the cylinders for combustion [5].

8. Diesel engine support systems

A diesel engine requires five supporting systems in order to operate cooling, lubrication, fuel injection, air intake, and exhaust. Depending on the size, power, and application of the diesel, these systems vary in size and complexity [5].

8.1. Engine cooling

Almost all diesel engines rely on a liquid cooling system to transfer waste heat out of the block and internals as shown in Figure I.15. The cooling system consists of a closed loop similar to that of a car engine and contains the following major components: water pump, radiator or heat exchanger, water jacket (which consists of coolant passages in the block and heads), and a thermostat.

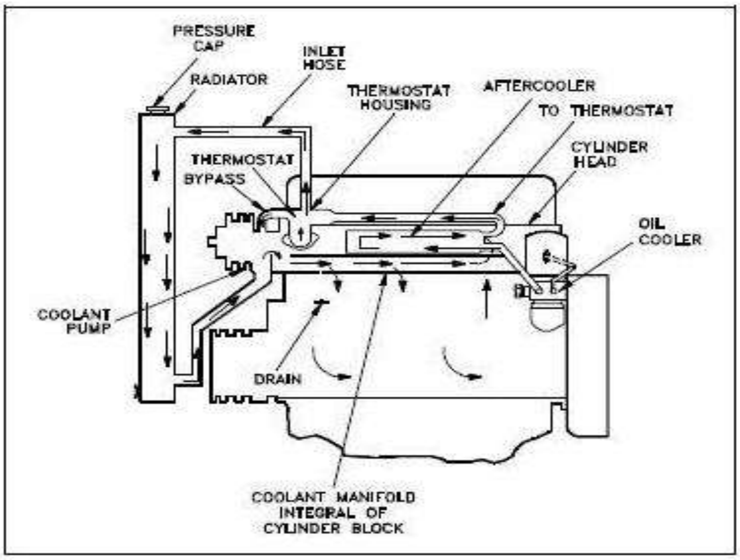

Figure I.15: Engine cooling system [5].

8.2. Engine lubrication

The oil serves two purposes. One purpose is to lubricate the bearing surfaces. The other purpose is to cool the bearings by absorbing the friction-generated heat. The flow of oil to the moving parts is accomplished by the engine's internal lubricating system. Oil is accumulated and stored in the engine's oil pan where one or more oil pumps take a suction and pump the oil through one or more oil filters as shown in Figure I.16. The filters clean the oil and remove any metal that the oil has picked up due to wear. The cleaned oil then flows up into the engine's oil galleries. A pressure relief valve(s) maintains oil pressure in the galleries and returns oil to the oil pan upon high pressure.

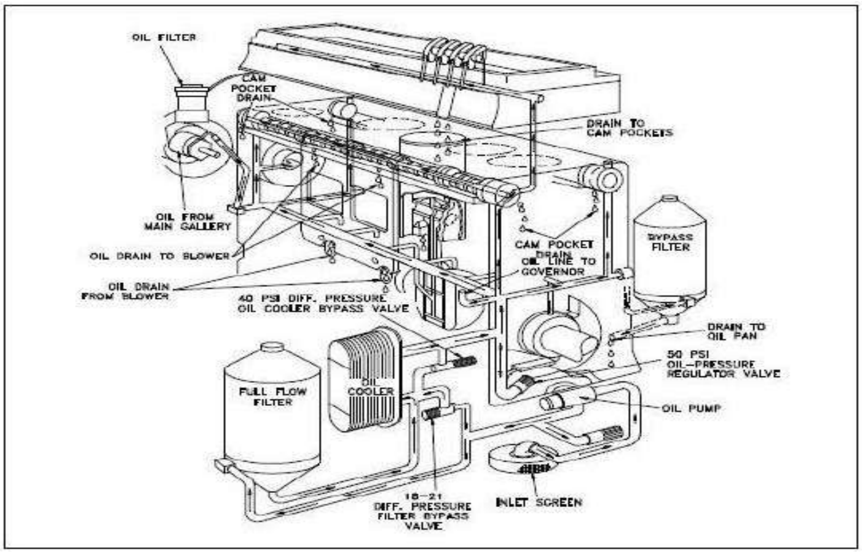

Figure I.16: Engine lubrication system [5].

The oil galleries distribute the oil to all the bearing surfaces in the engine. Once the oil has cooled and lubricated the bearing surfaces, it flows out of the bearing and gravity-flows back into the oil pan. In medium to large diesel engines, the oil is also cooled before being distributed into the block. This is accomplished by either an internal or external oil cooler. The lubrication system also supplies oil to the engine's governor, which is discussed later in this module.

8.3. Fuel system

In a diesel engine, the fuel system serves two purposes. The first purpose is obviously to supply the fuel to run the engine; the other is to act as a coolant to the injectors. To meet this second purpose, diesel fuel is kept continuously flowing through the engine's fuel system at a flow rate much higher than required to simply run the engine, an example of a fuel flowpath is shown in Figure I.17. The excess fuel is routed back to the fuel pump or the fuel storage tank depending on the application.

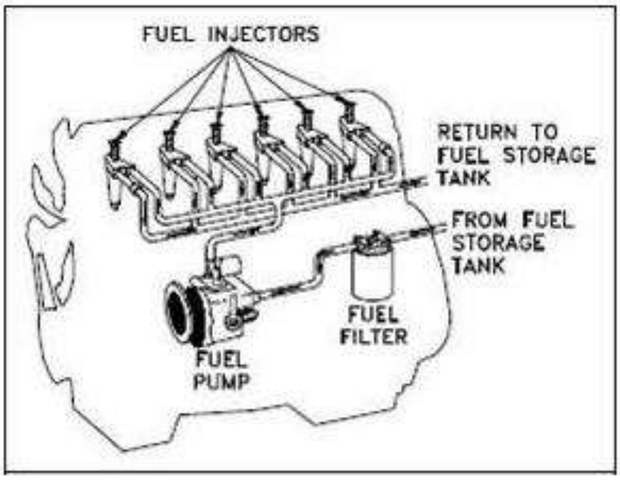

Figure I.17: Diesel engine fuel flow path system [5].

8.4. Air intake system

Air intake systems vary greatly from one to another but are usually one of two types, wet or dry. In a wet filter intake system, as shown in Figure I.18, the air is sucked or bubbled through a housing that holds a bath of oil such that the dirt in the air is removed by the oil in the filter. The air then flows through a screen-type material to ensure any entrained oil is removed from the air. In a dry filter system, paper, cloth, or a metal screen material is used to catch and trap dirt before it enters the engine (similar to the type used in automobile engines).

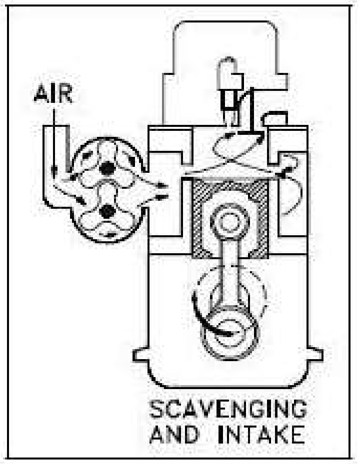

Figure I.18: Air intake system [5].

In addition to cleaning the air, the intake system is usually designed to intake fresh air from as far away from the engine as practicable, usually just outside of the engine's building or enclosure. This provides the engine with a supply of air that has not been heated by the engine's own waste heat.

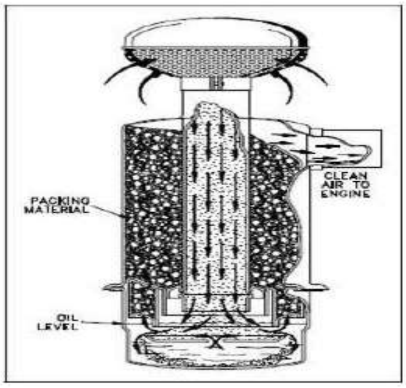

Figure I.19: Oil bath air filter [5].

After being filtered, the air is routed by the intake system into the engine's intake manifold or air box. The manifold or air box is the component that directs the fresh air to each of the engine's intake valves or ports. If the engine is turbocharged or supercharged, the fresh air will be compressed with a blower and possibly cooled before entering the intake manifold or air box. The intake system also serves to reduce the air flow noise.

8.5. Exhaust System

The exhaust system of a diesel engine performs three functions. First, the exhaust system routes the spent combustion gasses away from the engine, where the atmosphere dilutes them. This keeps the area around the engine habitable. Second, the exhaust system confines and routes the gasses to the turbocharger, if used. Third, the exhaust system allows mufflers to be used to reduce the engine noise.

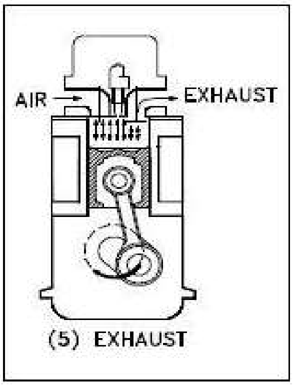

Figure I.20: Diesel engine exhaust system [5].

9. Conclusion:

Internal combustion engines are among the most important engineering applications. The diesel engine is an internal combustion engine that uses the heat of compression to ignite a fuel charge. Due to the method of ignition used, the reciprocating engines are commonly divided into two different categories, the spark ignition engines (SI-engine) and the compression ignition engines (CI-engine). Depending on the number of strokes required to complete one working cycle, internal combustion engines can be characterized as four-stroke or two-stroke cycle engine. This chapter introduces the history behind the diesel engine and the man that invented it, Rudolf Diesel. It also covers the basic operating principles of diesel engines and lays its major components. We also showed the supporting system of the diesel engine.

Chapter II

Hydrogen as alternative fuel

1. Introduction

For long time conventional fuels have been used for electricity, heating and transportation, however the concerns on fossil fuel depletion is urgently makes us work for research to find out the suitable alternative fuel. Alternative fuels is known as non-conventional fuels, which provide less pollution and more diversity of energy. Variety types of energy could be used as alternative fuel such as biodiesel, LPG, natural gas etc... Hydrogen is considered as a suitable substituting for traditional fossil fuels because of its emission performance.

This chapter goes into detail in describing an overview of the technologies used for hydrogen production from renewable sources, uses and storage. It will also highlight hydrogen as a secondary fuel for dual fuel technology. This chapter continues by going into detail in describing of hydrogen as alternative fuels. It also introduces the production, characteristics, environment effects of some alternative fuels, through an extensive literature reviews.

2. Renewable hydrogen as an alternative fuel

2.1. Renewable hydrogen

Hydrogen is the most abundant element present on earth. It is considered as a secondary form of energy it can be produced from any primary or renewable energy source [1], commonly referred to as an energy carrier. Energy carriers are used to move, store and deliver energy in a form that can be easily used. Electricity is the most well-known example of an energy carrier [8]. Hydrogen can be burned either to provide heat, or to drive turbines, or in internal combustion engines for motive and electrical power. The transport sector is also one of the fields of use of hydrogen as an energy carrier through electric vehicles powered by fuel cells [9] or directly mixed with other fuels such us CNG compressed natural gas [10].

2.2. Hydrogen discovery

After the Germans Kirchhoff und Bunsen had demonstrated in 1861 the presence of hydrogen in the spectra of the Sun, it became evident that hydrogen was the most abundant element in the Solar System. Hydrogen is the lightest element of the Periodic System.

After approximately 1800, the only significant application of hydrogen gas was for lighting and heating. A change came in the middle of the 20th century when natural gas was massively used for heating. In 1839 Sir William Grove constructed the first fuel cell. Although simple in principle the fuel cell remained for a century a curiosity since it turned out to be rather difficult to make a workable device out of it. The fuel cell of Grove did not even survive since another device made its apparition the internal combustion engine.

In 1909 Fritz Haber, a German chemist discovered a procedure to synthesize Ammonia (NH3) directly from the element H and N. Shortly later Carl Bosch, managed to adapt Haber's procedure to produce vast amount of ammonia. This provided Germany with a valuable source of material for explosives and fertilizers. [11]

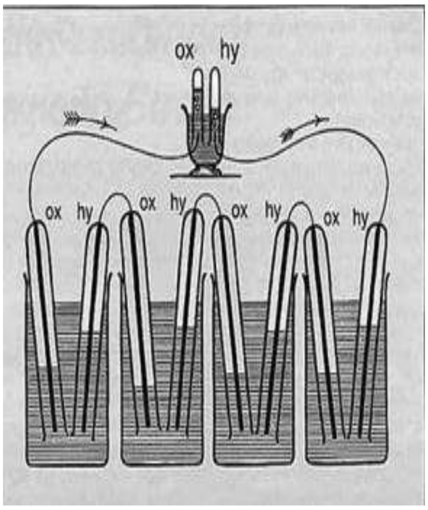

Figure II.1: Sir William Grove constructed hydrogen-filled the first fuel cell in 1938 [11].

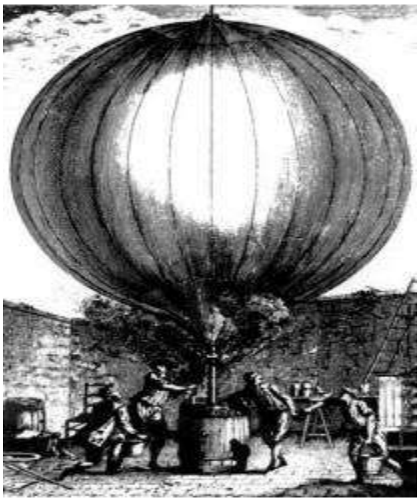

Figure II.2: Alexandre Cesar Charles with his William Grove constructed hydrogen-filled balloon in 1783 [11].

2.3. Hydrogen properties

First element in the periodic table. In normal conditions, it is a colorless, odorless and insipid gas, formed by diatomic molecules, H2. The hydrogen atom, symbol H, is formed by a nucleus with one unit of positive charge and one electron. Its atomic number is 1 and its atomic weight 1,00797 g/mol. It is one of the main compounds of water and of all organic matter, and it is widely spread not only in The Earth but also in the entire Universe. There are three hydrogen isotopes: protium, mass 1, found in more than 99,985% of the natural element; deuterium, mass 2, found in nature in 0.015% approximately, and tritium, mass 3, which appears in small quantities in nature, but can be artificially produced by various nuclear reactions [12].

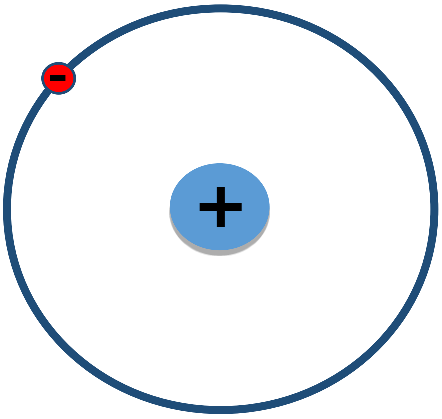

Figure II.3: The hydrogen atom.

2.4. Hydrogen production from renewable energy resources

Several techniques exist for the production of hydrogen. These include fossil resources, such as natural gas and coal, with only a couple being environmentally beneficial such as biomass and water with input from renewable energy sources (sunlight, wind, wave or hydropower). Hydrogen production technologies fall into three general categories: Electrolytic, biomass and thermochemical hydrogen production. This subsection gives an overview of the main characteristics of the production. Therefore, technologies that uses nonrenewable energies such as steam reforming of hydrocarbons, gasification of coal and nuclear will not be considered [3].

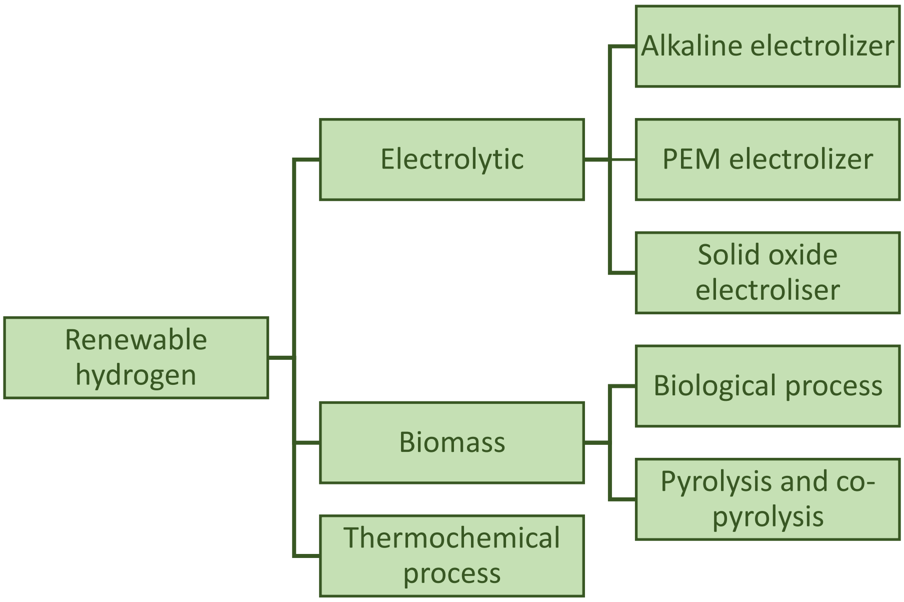

Figure II.4: Some alternative processes for hydrogen production.

2.4.1. Electrolytic hydrogen production

Electrolytic processes use electricity to split water into hydrogen and oxygen in a unit called an electrolyzer. Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte. Of all the hydrogen production technologies, Water electrolysis is compatible with large variety of available renewable energy technologies namely, solar, hydro, wind, wave, geothermal, etc. The chemical reaction of electrolysis process is as follows [13]:

$$H_2O \rightarrow 2H_2 + O_2 \qquad (1)$$

There are three main methods based on water electrolysis [13]:

a. Alkaline electrolyzer

The most common electrolysis technologies are based on the electrolysis of alkaline solutions. In the alkaline electrolyzer, water is fed into the cathode, where it is disassociated into hydrogen and hydroxyl ions (OH-), which pass through electrolytic material to the anode, where oxygen is, formed

$$Cathode: \quad 2H_2\mathrm{O} + 2e^- \rightarrow \ H_2 + 2OH^- \qquad (2)$$

$$Anode: \quad 4OH^- \rightarrow \ O_2 + 2H_2O \qquad (3)$$

$$Total: \quad H_2O \rightarrow \ H_2 + \frac{1}{2}O_2 \qquad (4)$$

Hydrogen leaves an alkaline solution and is separated from water in a gaseliquid separation unit outside of the electrolyzer.

b. polymer electrolyte membrane electrolyzer

Water in the PEM electrolyzer is fed to the anode, where it is split into a hydrogen cation and oxygen. The hydrogen cations pass through the polymer membrane to the cathode. At the cathode, the hydrogen cations are compatible with the electrons flowing from the outer circuit, which results in the creation of gas hydrogen:

$$Anode: \quad 2H_2O \rightarrow \ O_2 + 4H^+ + 4e^- \qquad (5)$$

$$Cathode: \quad 4H^+ + 4e^- \rightarrow 2H_2 \qquad (6)$$

The total is the same as for the alkaline electrolyzer :

$$Total:\quad H_2O \rightarrow\ H_2 + \tfrac{1}{2}O_2 \qquad (7)$$

c. Solid oxide electrolysis cells

Solid oxide electrolysis cells are essentially the solid oxides of fuel cells which use a solid material as an electrolyte. The electrolyte selectively transfers oxygen anions at increased temperature. SOEC work like the alkaline system, because the oxygen ion passes through the electrolyte while leaving hydrogen in a non-reactive flow of steam. The SOEC work at high temperatures of 500-800 °C in comparison with PEM electrolyzers, which work at temperatures of 80-100 °C, and alkaline electrolyzers, which work in the temperature range of 100-150 °C.

2.4.2. Hydrogen production from biomass

a. Biological process

The majority of hydrogen production researches focused on using biohydrogen fuel because of the rising amount of waste materials and the need for their minimization. The major criteria for the selection raw materials are cost, content of carbohydrate, biodegradability and availability. Biological processes usually work with various types of the anaerobic bacteria or algae. The effect of the microorganisms differs from one another by the type of substrate and the process conditions.

Biological hydrogen production as a byproduct of the metabolism of the microorganisms includes newly developed technologies utilizing various renewable resources, which can be divided into five separate categories: direct biophotolysis, indirect biophotolysis, biological wateregas conversion, photofermentation and dark fermentation. Enzymes producing hydrogen, particularly nitrogenase and hydrogenase, control all of these processes. The creation of hydrogen by nitrogenase can be described by the chemical reaction [13]

$$4ATP + 2H^+ + 2e^- \rightarrow H_2 + 4ADP + 4Pi \qquad (8)$$

b. Pyrolysis and co-pyrolysis

Another currently promising method of hydrogen production is pyrolysis, or co-pyrolysis raw organic material is heated and degasified at a certain pressure and temperature. The process takes place in the absence of oxygen as well as air, and therefore the formation of dioxins can be almost ruled out. As a result a significant lowering of emissions is achieved. The reaction can be generally described by the following equation [13]:

$$Organic\ material + Heat \rightarrow H_2 + CO + CH_4 + Other\ products \quad (9)$$

2.4.3. Thermo-chemical water splitting

Thermo-chemical water splitting is the conversion of water into hydrogen and oxygen by a series of thermally driven chemical reactions. Figure II.5 shows an example of principle drawing of iodine/sulfur thermo-chemical process [3]:

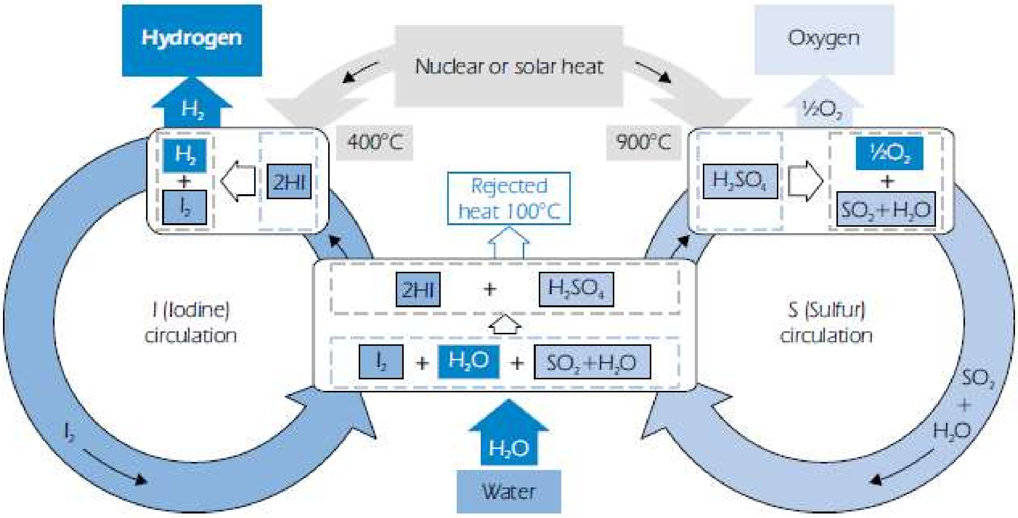

Figure II.5: Principle drawing of iodine/sulfur thermo-chemical process [3].

3. Hydrogen storage

In the current state-of-the-art in hydrogen storage, no single technology satisfies all of the criteria required by manufacturers and end-users, and a large number of obstacles have to be overcome [14]. The current hydrogen storage technologies and their associated limitations/needs for improvement are:

- Compressed hydrogen: The storage of hydrogen in gaseous form is the most common method. To increase its volumetric energy density, the hydrogen gas is compressed under high pressure up to 700 bar. This requires about 20% energy loss during compression and severe safety requirements, and on the other hand, cost penalties related to the quantity and price of the composite material. to be used for strengthening the structure of the storage tank [15].

- Liquid hydrogen: The hydrogen is converted from its gaseous state to the liquid state by cooling it to a temperature of 20 K at atmospheric pressure. Although the volumetric capacity of hydrogen in this state is higher than that in the gaseous state (70 kg / m3 compared to 39 kg / m3 for storage at 700 bar), storing hydrogen at this low temperature results in unavoidable thermal losses and daily evaporation of the stored hydrogen, reduced to 1% per day for a super isolated system. The major disadvantage of liquid storage is the energy required for the liquefaction of hydrogen, representing 30% of its lower heating value, which seriously penalizes the overall efficiency of this storage mode [15].

- Metal hydrides: metal hydrides store hydrogen by chemically bonding the hydrogen to metal or metalloid elements and alloys. Hydrides are unique because some can adsorb hydrogen at or below atmospheric pressure, and then release the hydrogen at significantly higher pressure when heated. There is a wide operating range of temperatures and pressures depending on the alloy chosen. Each alloy has different performance characteristics, such as cycle life and heat of reaction. Metal hydrides offer the advantages of lower pressure storage, conformable shapes, and reasonable volumetric storage efficiency, but have weight penalties and thermal management issues. There is a need to rationalize overall research efforts by sharing expertise, specific equipment and modelling tools for systems validation and improvements concerning weight and activation treatments [14].

- Carbon-based materials/porous structures can also store significant amounts of hydrogen at room temperature because of their high surface area and abundant pore volume. The most recently discovered nanomaterial such as single-walled nanotubes and graphite nanofibers have renewed attention on carbon as an adsorbent, which has the advantage of being inherently safe. Nevertheless, on a fundamental level there are still challenges on understanding the exact adsorption/desorption mechanism and the volumetric capacity of porous structures. It is also recognized that there is a need for comparison and validation of hydrogen storage measurements in order to avoid dissemination of unreliable results [15].

4. Hydrogen use

Hydrogen can be burned either to provide heat, or to drive turbines, or in internal combustion engines for motive and electrical power. It is used in a wide variety of applications: ammonia and fertilizer manufacturing, poly-silicon production, margarine manufacturing, power plant cooling, etc. The transport sector is also one of the fields of use of hydrogen as an energy carrier through electric vehicles powered by fuel cells [9] or directly mixed with CNG compressed natural gas [10].

4.1. Hydrogen as Fuel Cells

Fuel cells convert the chemical energy in hydrogen directly to electricity and heat. Inside a fuel cell, hydrogen electrochemically combines with oxygen from the air to create electricity, with pure water and potentially useful heat as the only byproducts. Hydrogen powered fuel cells are not only environmental, but also can have tougher efficiency of traditional internal combustion technologies. In normal driving, the gasoline engine in a conventional car is less than 20% efficient in converting the chemical energy in gasoline into power that moves the vehicle. Hydrogen fuel cell vehicles, which use electric motors, are much more energy efficient and use up to 60% of the fuel's energy [8].

4.2. Hydrogen as an electric bridge

In the future, hydrogen could also join electricity as an important energy carrier. An energy carrier moves and delivers energy in a usable form to consumers. Renewable energy sources, like the sun and wind, cannot produce energy all the time. However, they could, for example, produce electric energy and hydrogen, which can be stored until it is needed. Like electricity, hydrogen can also be transported to locations where it is needed [9].

5. Dual fuel

Dual fuel engine works on a diesel cycle, as the name implies two fuels come into use. This operation use a mixture of liquid fuels (pilot fuel) such us diesel oil or gas oil and gaseous fuels (the primary fuel) such natural gas, hydrogen or LPG.

5.1. Dual fuel working principal

The dual fuel engine works on compression ignition principle. At first the air-fuel is drawn into the engine cylinder which is highly compressed in the cylinder. Next step is the ignition process. However, this fuel (also called gaseous fuel) is not a good compression ignition fuel. Hence a small amount of diesel (called as pilot fuel) is injected, which acts as a catalyser to the ignition process. As the fuel is ignited due to the temperature rise, the whole air-fuel mixture ignites and rapid combustion takes place. Due to this rapid combustion the pressure inside the cylinder is increased causing the piston to move and produce engine power [17].

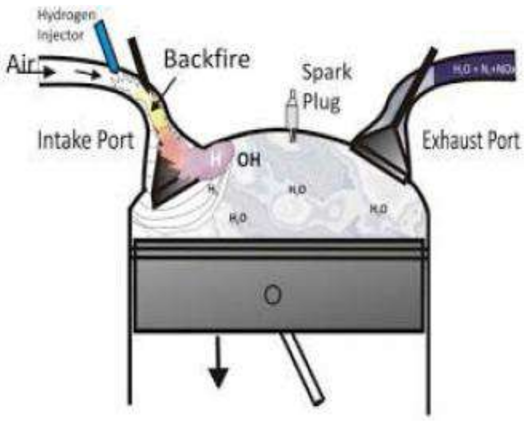

Figure II.6: Dual fuel operation [1]

5.2. Dual fuel injection system

Hydrogen fuel delivery system can be divided into 3 major types [1]:

5.2.1. Hydrogen direct injection technique

In direct injection, air-fuel is injected directly into the combustion cylinder during the compression stroke when the intake valve is closed. As hydrogen diffuses quickly, the mixing of hydrogen takes flame instantaneously. A schematic diagram illustrating the operation of direct injection is shown in Figure II.7.

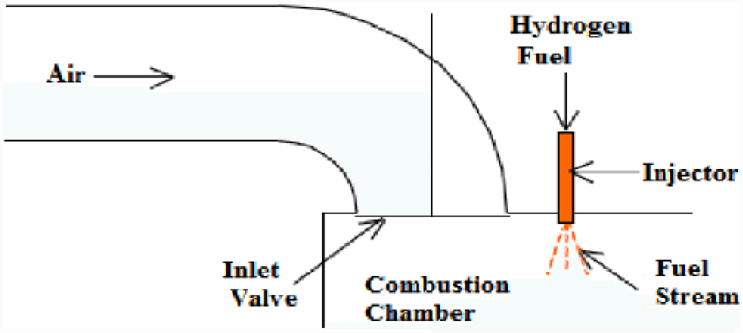

Figure II.7 : Hydrogen direct injection [1].

5.2.2. Hydrogen indirect injection technique

The port injection fuel delivery system consists of an injection of fuel directly into the intake manifold each intake port rather than drawing fuel in at a central point. After the beginning of the intake stroke, the hydrogen is injected into the manifold. The air is injected separately at the beginning of intake stroke to dilute the hot residual gases results the less pre-ignition. The inlet supply for port injection is higher than for central injection but less than for direct injection systems. A schematic diagram illustrating the operation of inlet port injection is shown in Figure II.8.

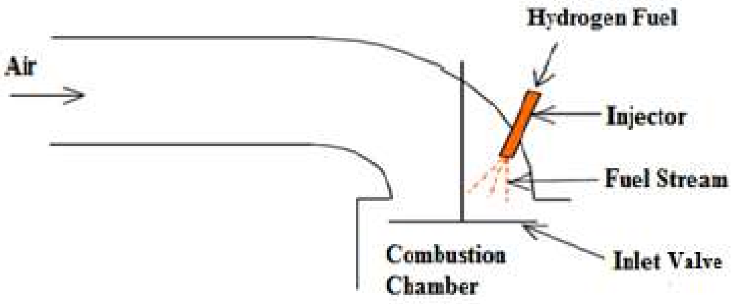

Figure II.8: Hydrogen indirect injection [1].

5.2.3 Central injection or carbureted system

This is the simplest method of delivering fuel to hydrogen engine. The central injection is made at the inlet of the air intake manifold. Carbureted system it does not require high value of hydrogen supply pressure to be as high as for other methods and can be easily converted in to hydrogen engine. A schematic diagram illustrating the operation of Carbureted injection system is shown in Figure II.9.

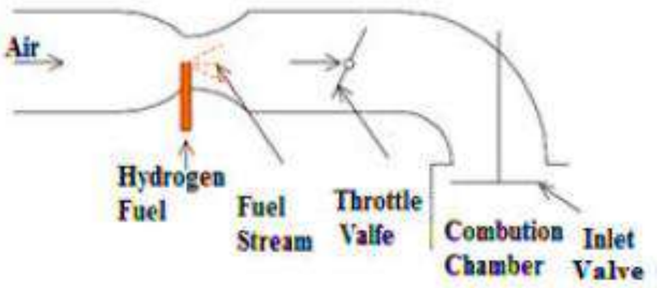

Figure II.9: Hydrogen central injection [1].

6. Review of experimental and theatrical investigations of other alternative fuels

The combustion of fossil fuels in IC engines and its harmful impacts effects on the environment and human health is urgently makes us work for research to find out the viable alternative fuels. In order to face this challenge, there has been an enormous amount of research that has been done concerning use of alternative fuels in dual fuel engines. Here is some experiments that were conducted to evaluate the performance emission and combustion parameters in a compression ignition engine primarily fuelled with an alternative fuel.

6.1. Natural gas

Natural gas is fossil fuel based energy which is unsustainable but can be used to substitute petrol. It is a hydrocarbon gas, which mix with methane-carbon dioxide, and nitrogen. Natural gas can be found in underground coal bed or oilfield and often used for heating, cooking, and generating electricity [10]. Natural gas uses in two major forms: 'one is Liquefied Natural Gas (LNG), which is produced by purifying natural gas and super-cooling it to turn it into a liquid, this process known as liquefaction' [18]. the other is 'Compressed Natural Gas (CNG, which is formed deep underground trapped between layers of rock and sand in reservoirs underneath the Earth, like other fossil fuels)' [19].

Miqdam Tariq [20] investigated the performance characteristics of single cylinder diesel engine Ricardo E6 run with natural gas and diesel in dual fuel mode. His results showed the

brake specific fuel consumption under dual fuel conditions, was higher than original diesel operation for evaluated engine speeds at very lean equivalence ratios and low loads, at higher equivalence ratios with higher loads and NG substitution, dual fuel engine performance was poorer. Lean operation with low loads resulted in poor fuel utilization and power output, and it reduced the efficiency.

The investigation of Egúsquiza et al. [10] reported a significantly decreases of the NOx emissions in the natural gas/ diesel engine. However, the hydrocarbon (HC) and carbon monoxide (CO) emissions increased even more than those of the original Diesel engine, Wong et al [20] explained that this increasing is due to engine knocking which results in lower combustion efficiency. This is also due to the fact that engine knocks become apparent when the engine is operating under high load conditions. Theses concentrations increased with substitution ratio and a reduction is observed only under high load conditions and high substitution ratios [10].

6.2. Biodiesel

Biodiesel is an alternative fuel that is produced by chemically combining vegetable oils and animal fats with an alcohol to form alkyl esters. Extensive research and demonstration projects have shown it can be used pure [21] or in blends with conventional diesel fuel [22]. Beside this methyl esters of fatty acids or biodiesel have several outstanding advantages among other non-renewable and clean engine fuel alternatives and can be used in any diesel engine without any modification. Biodiesels offer a very promising alternative to diesel oil since they are renewable and have similar properties with fossil Diesel [23].

Biodiesel can be produced in many ways, including; Pyrolysis, Micro emulsification, Dilution and Transesterification. Among these, transesterification is the most commonly used commercial process to produce clean and environmentally friendly light vegetable oil fuel (biodiesel), transesterification is a chemical reaction whereby the glycerin is separated from the fat or vegetable oil. [23].

Avinash Kumar et al. [24] used four-stroke, single cylinder diesel engine to study the effect of biodiesel blends on performance of the engine. Their experiments were conducted at 200 bars fuel injection pressure and compared the performance of 20% and 100% biodiesel blends with original diesel. BSFC for NB100 and NB 20 was higher than original diesel. BSFC was observed to be increased with increasing proportion of biodiesel in the fuel.

Most researchers results show a sharp decrease in CO emissions [25, 26], also for hydrocarbon emissions [22, 25, and 26] when substituting conventional diesel fuel with biodiesel fuels as shown in Fig. (4, 5). Most of the authors have attributed this to better combustion in biodiesel-fuelled engines. Since biodiesel is an oxygenated fuel, it promotes combustion and results in the reduction of UBHC emissions. For the NOx Most of the earlier investigations show that NOx emission from biodiesel engines are generally higher than that in conventional diesel fueled engines. Also earlier investigations revealed that NOx emissions increase with an increase in the biodiesel content of diesel. They conclude this is due to higher combustion temperatures and longer combustion duration [26, 21].

6.3. Liquefied petroleum gas

Liquefied petroleum gas (LPG) is a mixture of various hydrocarbons and its main components are either propane (C3H8) or butane (C4H10), or combination of the two. LPG is a widely used alternative fuel; it is a multi-purposed fuel, which can be used as the burning fuel in transportation, industrial application, agricultural, leisure industry, cooking and space heating which currently drive from crude oil or natural gas [28].

LPG has two origins approximately 60% is recovered during the extraction of natural gas and oil from the earth, and the remaining 40% is produced during the refining of crude oil, which produced at various stages: atmospheric distillation, reforming, cracking and others. LPG is thus a naturally occurring by-product [29].

K F Mustafa's investigation of a liquefied petroleum gas (LPG) shows that the carbon monoxide (CO) exhibits a sharp decreased as the relative air-fuel ratio increases. Unburned hydrocarbons

(UHC) also shows marked reduction as the relative air-fuel ratio exceeds stoichiometric, However, nitrogen oxides (NOx) exhibits an increasing trend as the relative air-fuel ratio increases [30].

7. Conclusion

Although hydrogen is the most abundant element in the universe, it does not naturally exist in its elemental form on earth. This chapter offers an overview of the technologies used for hydrogen production. The technologies discussed are only environmentally beneficial processes such as biomass and electrolytic with input from renewable energy sources (sunlight, wind, wave or hydropower). The section continues by overviewing various storage modes available for the hydrogen. After that, we highlighted hydrogen as a secondary fuel for dual fuel technology. A detailed literature review is summarized which contains an introducing of the production, characteristics, environment effects of some alternative fuels.

Chapter III

Effect of hydrogen-diesel performance on a dual-fuel engine

1. Introduction

The increasing demand of fossil fuels is urgently makes us work for research to find out the viable alternative fuels for meeting sustainable energy demand with minimum environmental impact. The internal combustion engines emit many pollutants like hydrocarbons, nitrogen oxides, carbon monoxide and carbon dioxide, which can lead to cancer, acid rain, heart disease and global warming, respectively. Due to the increasing of harmful exhaust emissions, working on alternative power systems has become a high priority for governments. The use of hydrogen as a fuel for internal combustion engines, either alone or in combination with other fuels such as Diesel or LPG, has been given much attention because of its possible environmental over fossil fuel.

In this chapter, we will examine the effect of dual fuel combustion on the performance and emission characteristics of a Caterpillar3512 diesel engine converted to dual fuel engine by using hydrogen as alternative fuel. After that, we will describe the design and the operating principle of the hydrogen production plant, and then we will present the dimensioning of the different subsystems to compose the REn/H_2 system: we will start with the production subsystem of renewable electric energy followed by electrolyser subsystem. Finally an economic optimization by considering several configurations using a numeric code in Matlab language for estimating the cost of the REn/H_2 system.

2. Engine description

Caterpillar 3512 engine is four-stroke diesel engine, with 3500 series and 12 cylinders V; supercharged by two turbochargers driven by the engine exhaust, which run at a speed of 45,000 to 60,000 rpm. Each cylinder has two intake valves and two exhaust valves. The camshaft mechanically actuates the rockers and the valves via pushers. The diesel is injected directly into the cylinder. An electric regulator and a control mechanism control the flow of the injection pump to maintain the engine speed chosen by the operator. The injection pump combines the dosing and pumping of diesel, which is fed to the injectors. Automatic timing advance ensures optimal injection in any engine speed range. The air filter filters the intake air. The air is compressed by the Turbo-compressor before entering the cylinders. Turbo-compressor is driven by engine exhaust. The engine is supercharged and inter-cooled. The water pump in the cylinder block circulates the coolant liquid [31].

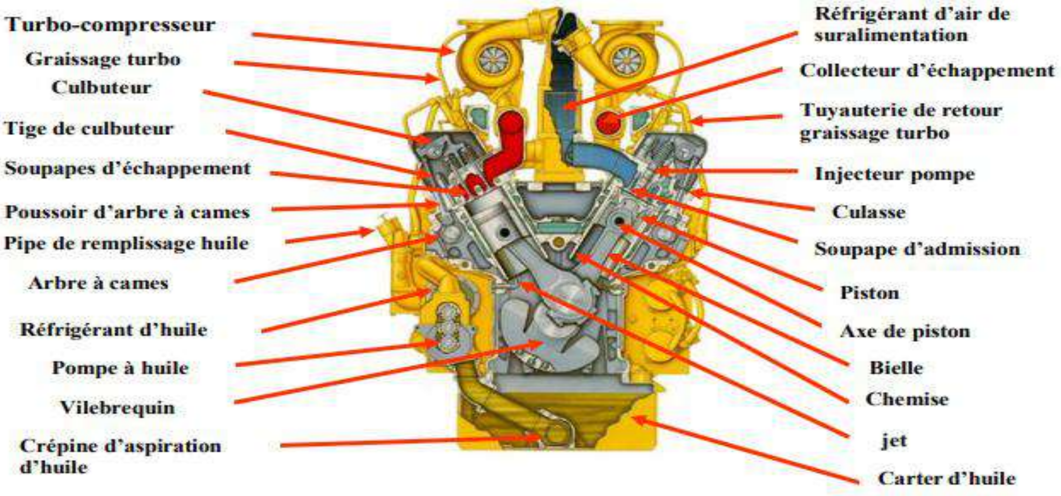

Figure III.1: Description of the Caterpillar 3512 engine [31].

3. Performance evaluation of engine

The engine used in the present study is four-stroke Caterpillar 3512 with a direct injection, This engine is the common primary engine for drilling rigs and can be operate with a blend of hydrogen and diesel fuel which is known as dual-fuel technology. The engine can be substituted between diesel and hydrogen automatically, while maintaining all engine parameters. Table III.1 summarizes the main parameters of the engine operation:

Table III.1: General specification of the Caterpillar 3512 diesel engine [31].

Item	Specification	Unite
Effective power	1175	**kW**
Rotation speed	1200	**rpm**
Slow speed	900	**rpm**
Flow rate of the diesel pump	21	**min/l**
Specific consumption	204.5	**g/kWh**
Flow rate of the water pump	1520	**l/min**
Number of cylinders	12	**/**
Bore x stroke	0.17 m x 0.19 m	**m**
Compression ratio	14	**/**
Maximum engine torque	9603	**N.m**
Cylinder unit capacity	4.3	**l**
Total cylinder capacity	51.8	**l**

The objectif of our study is to calculate   for each operating condition (load, substitution ratio). A schematic diagram showing engine arrangement including hydrogen delivery and exhaust emissions instrumentation in Figure III.2.

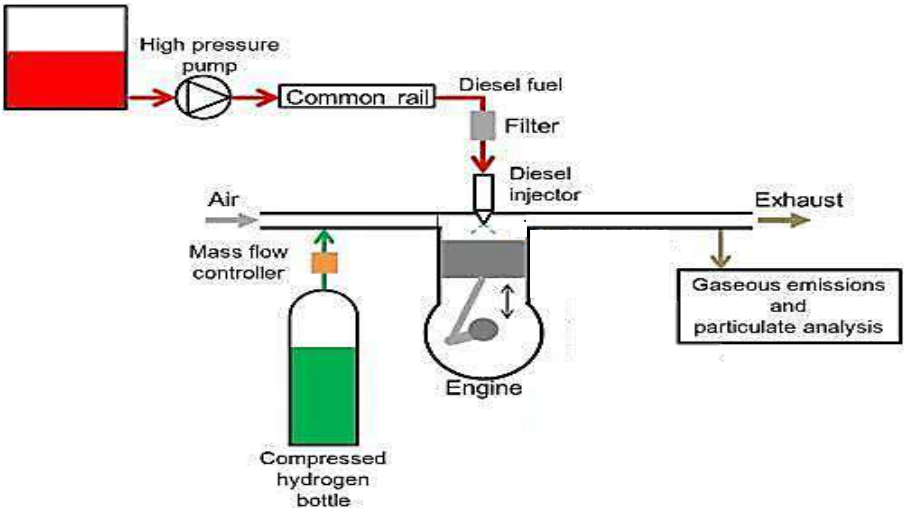

Figure III.2: Dual-fuel engine operation [32].

3.1. Stoichiometric air quantity

3.1.1. Diesel combustion

The combustion of 1 kilogram of diesel fuel needs about 14.6 kilograms of air (that is, given the composition of the air, about 11.2 kilograms of nitrogen and 3.4 kilograms of oxygen). The reaction produces about 11.2 kilograms of nitrogen (this gas being chemically neutral, it did not participate in the combustion), 3.2 kilograms of carbon dioxide (CO2) and 1.2 kilograms of water (H2O) [33]. The chemical reaction of fuel combustion is given as follows:

$$C_{7.25}H_{13} + 10.5O_2 + (10.5 + 3.8)N_2 \rightarrow 7.25CO_2 + 6.5H_2O + 40N_2 \qquad (1)$$

3.1.2. Hydrogen combustion

Stoichiometric fuel is the quantity of air required for complete combustion of 1kg of fuel without any oxygen appearing in the products of combustion. The combustion of hydrogen and oxygen is given as [2]:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (2)$$

Two moles of H_2 required for complete combustion.

One moles of O_2 required for complete combustion.

Because air is used as the oxidizer instead of oxygen, the nitrogen in the air should be included:

Moles of N_2 in air = Moles of O_2 x (79% N_2 in air / 21% O_2 in air)
= 1 mole of O_2 x (79% N_2 in air / 21% O_2 in air)
= 3.762 moles N_2

Number of moles of air = Moles of O_2 + Moles of N_2
= 1 + 3.762
= 4.762 moles of air

Weight of O_2 = 1 mole of O_2 x 32 g/mole
= 32 g

Weight of N_2 = 3.762 moles of N_2 x 28 g/mole
= 105.33 g

Weight of air = weight of O_2 + weight of N_2
= 32g + 105.33 g
= 137.33 g

Weight of H_2 = 2 Moles of H_2 x 2 g/mole
= 4 g

Stoichiometric air/fuel (A/F) ratio for hydrogen and air is:

A/F based on mass = mass of air/mass of fuel
= 137.33 g / 4 g
= 34.33

As these calculations show, the stoichiometric A/F ratio for the complete combustion of hydrogen in air is about 34 by mass. This means that for complete combustion, 34 pounds of air are required for every pound of hydrogen.

3.2. Hydrogen as an energy carrier

Hydrogen is the most abundant element present on earth. It is considered as a secondary source of energy, commonly referred to as an energy carrier. The ever-increasing demands for fossil fuels have left us with very miniscule reservoirs with the increasing in global warming due to the emission matter to the atmosphere. Hydrogen is considered as an important energy carrier in the future it has a number of advantages. It is not a pollutant and does not contaminate the ground water [2]. Hydrogen has many unique physical properties including low molecular weight, large diffusion coefficient, high thermal conductivity, and low viscosity. Hydrogen has many advantageous combustion properties including high flame speed, small quenching distance, low ignition energy, high auto ignition temperature, and high octane. Table III.2 shows a comparison between some basic properties for hydrogen and diesel:

Table III.2: Comparison between diesel-hydrogen properties [34].

Fuel property	**Diesel**	**Hydrogen**	**Unite**
Chemical formula	$\approx C_{12}H_{25}$	H_2	/
Density	815	0.08988	**kg/m^3**
molecular weight	170	2.016	**kg/kmol**
Lower heating value	42.5	119.96	**MJ/kg**
Stoichiometric air-fuel ratio	14.6	34.3	/
Ignition temperature	355	500	**˚C**
Adiabatic flame temperature	1720	2210	**˚C**
Sulfur content by weight	0.5	0	**%**

3.3. Fuel substitution

In order to calculate the percentage of diesel/hydrogen fuel substitution, the equation (3) was used [10]:

$$S_{D/H_2} = \left[1 - \left(\frac{\dot{m}_D}{\dot{m}_{H_2}}\right)\right] \tag{3}$$

Where:

$\dot{m}_D$	Diesel masse; kg/h
$\dot{m}_{H_2}$	Hydrogen fuel masse; kg/h

The total fuel-air equivalence ratio is defined as the ratio of the mass of the stoichiometric amount of air required both for combustion of hydrogen and the diesel to the mass of the actual amount of air consumed by the engine [10]:

$$\emptyset_T = \frac{14.6\dot{m}_D + 34.3\dot{m}_{H_2}}{\dot{m}_{air}} \tag{4}$$

Where:

$\dot{m}_{air}$	The mass flow rates of air; kg/h.
34.3	The air mass flow required for the stoichiometric and complete combustion of 1kg of natural gas used.
14.6	The air mass flow required for the stoichiometric and complete combustion of 1kg of diesel used.

In order to determine the thermal efficiency of engine on dual fuel mode, the formula (5) will be used [10]:

$$\eta_t = \frac{Brake\ power}{Power\ inpot\ from\ pilot\ diesel + Power\ input\ from\ hydrogen} \quad (5)$$

Power input by diesel or hydrogen will be determined using the following equation [35]:

$$P_a = LHV_a . C_a \quad (6)$$

Where:

P	Power input; kW
LHV	Lower heating value; kJ/kg
C	Consumption; kg/h
a	Fuel type

The results we obtain of using different Hydrogen /Diesel ratios on the Caterpillar 3512 engine operating at 80% of nominal power are presented in the following table:

Table III.3: Characteristics of the Caterpillar 3512 engine operating at 80% of nominal power with different diesel / hydrogen ratios.

S_H (%)	S_D (%)	$\dot{m}_{GDF}$ (Kg/h)	$\dot{m}_{Gsub}$ (Kg/h)	$\dot{m}_H$ (Kg/h)	P_D (kWh)	P_H (kWh)
0	**100**	192.23	0	0	2269.38	0
10	**90**	173.01	19.22	6.81	2042.44	226.94
20	**80**	153.78	38.45	13.62	1815.51	453.88
30	**70**	134.56	57.67	20.43	1588.57	680.81
40	**60**	115.34	76.89	27.24	1361.63	907.75
50	**50**	96.12	96.12	34.05	1134.69	113469
60	**40**	76.89	115.34	40.86	907.75	1361.63

Calculations were carried out with hydrogen and diesel in dual fuel operation for each operating condition (load, substitution ratio). First, we calculated the engine performance characteristics on pure diesel. After that, similar calculations were recorded on pure diesel and hydrogen blend).

3.4. Specific Fuel Consumption of a cat 3512 engine

Likewise, under dual fuel operation, the effective Specific Fuel Consumption (SFC) was estimated from the fuel mass flow rates per unit power output [10]:

$$SFC = [\frac{(\dot{m}_D+\dot{m}_{H_2}).1000}{P}] \qquad (7)$$

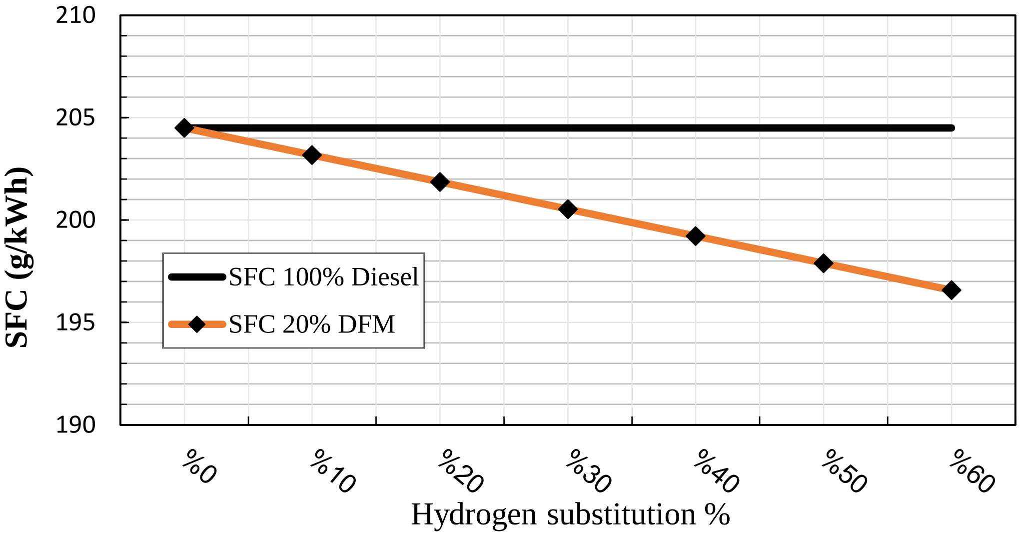

Figure III.3: Variation of SFC for different substitution ratios.

Figure (III.3) provides the variation of the equivalent of Specific Fuel Consumption (SFC) as a function of hydrogen substitution ratio for various loads at 1200-rpm engine speed. SFC for dual fuel operation is computed from the sum of hydrogen and diesel fuel consumed. As shown the specific fuel consumption for dual fuel operation decreased with the increase of hydrogen addition, for example at 20/80 of (hydrogen/diesel) substitution, SFC is noticeably lower up to 7.31% compared to original diesel operation at load of 80%. This reduction in the specific consumption is due to the Lower Heating Value (LHV) of hydrogen is higher than that of diesel.

4. Effect of dual fuel operation on emissions

The product of combustion of air fuel mixture contains several constituents that are considered hazardous to human health, including carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NO_x), and carbon dioxide (CO_2). The concentration of gaseous emissions in the engine exhaust gases are usually measured in parts per million (ppm) or percentage (%) by volume [2].

For most emission sources, the following equation is used [36]:

$$Emission = \sum_a [Fuel_a \times EF_a] \tag{8}$$

Emission	the emission of HC, CO, CO_2, NO_X, kg
Fuel	Fuel consumption, toe
EF	Emission factor, kg/toe

The emission factors are determined from the physical composition of the fuel consumed and its calorific value. The table below represents emission rates for each fuel type:

Table III.4: Emission Factors for Fuels Diesel / Hydrogen [36].

Fuel type	HC (g/kWh)	CO (g/kWh)	CO_2 (kg/h)	NOx (g/kWh)
Diesel	1.1	4.00	3.2	7.00
Hydrogen	0.00	0.00	0.00	≈00

Our studies were calculated at speed of 1200 rpm, and at 40%, 50%, 60%, 70% and 80% engine loads. At each engine load, estimations were carried out for diesel / hydrogen fuel on emissions included HC, CO, CO_2, and NO_x.

4.1. Hydrocarbons emission

Unburned hydrocarbons HC can adversely affect human health. Certain HC's are also considered carcinogenic. The principal cause of HC is incomplete combustion of the fuel-air charge, resulting in part from flame quenching of the combustion process at the combustion chamber walls, and engine misfiring. The scavenging process often results in a portion of the fresh mixture exiting the exhaust port before it closes, resulting in large HC emissions. Engine variables that affect HC emissions include the fuel-air ratio, intake air temperature, and cooling water temperature [37]. The variation of the hydrocarbon emission at different engine load conditions of the dual fuel engine is presented below.

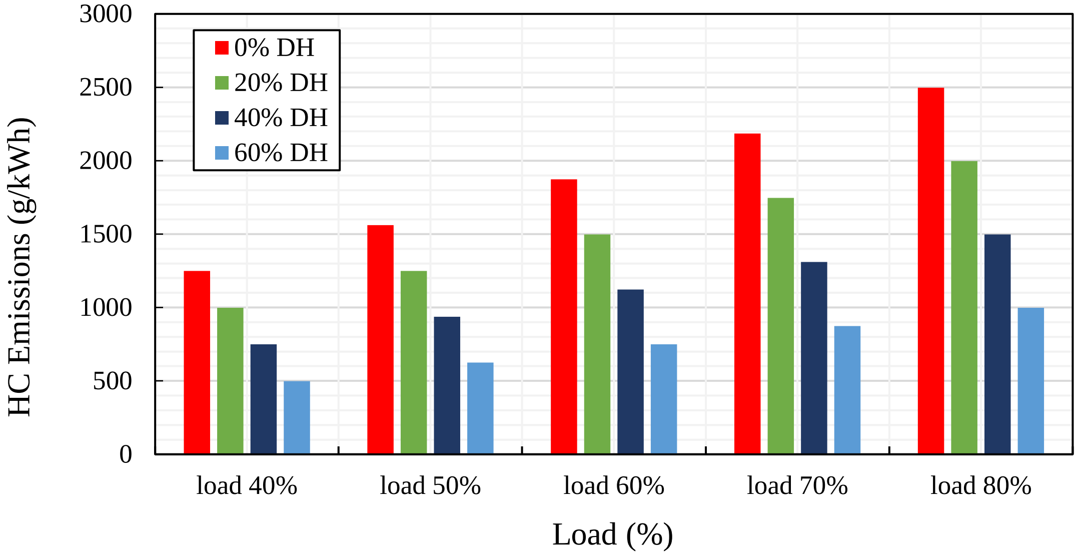

Figure III.4: Effect of dual fuel and engine load on hydrocarbon emission.

As shown in Figure III.4, for diesel, the HC emission decreases with the increases of hydrogen addition. At 40%, 60% and 80% load hydrocarbons emission reduces by 259.63 g/kWh, 374.45 g/kWh and 499.26 g/kWh respectively. Condition with 20% of hydrogen addition. This reduction is due to the increase in combustion temperature associated with higher engine load.

4.2. Carbon monoxide emission:

Carbon monoxide CO is a colorless, odorless, and tasteless gas that is highly toxic to humans. Breathing air with a small volumetric concentration (0.3%) of CO in an enclosed space can cause death in a short period. CO results from the incomplete combustion of hydrocarbon fuels [37]. Figure III.5 represent the effect of dual fuel and engine load on CO emission.

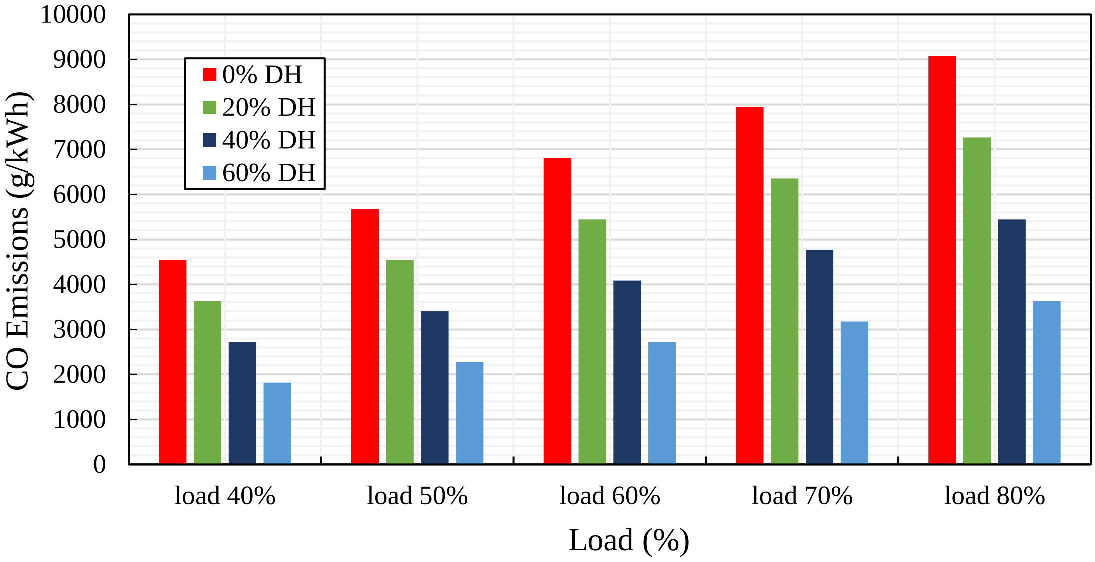

Figure III.5: Effect of dual fuel and engine load on CO emission.

The characteristics of CO emission are shown in Figure III.5. The CO formation reduces with the addition of hydrogen. It has been observed that the reduction of CO emission for hydrogen/diesel (20/80) dual fuel blend reduces by 907.75 g/kWh, 1361.93 g/kWh and 1815.50 g/kWh at load of 40%, 60% and full load 80% respectively as compared to the emission of diesel fuel alone.

4.3. Carbone dioxide emission

Carbon dioxide emissions in diesel engines are products of direct combustions or by-product of oxidizing other unwanted emission gases with the aid of catalysts. Although diesel engines generally produce, low amounts of CO_2 compared to other emission gases. The emission of carbon dioxide must be regulated and controlled to reduce negative impacts on the environment such as accumulation of greenhouse gases and global warming [37]. The effect of dual fuel and engine load on CO2 emission is presented in Figure III.6.

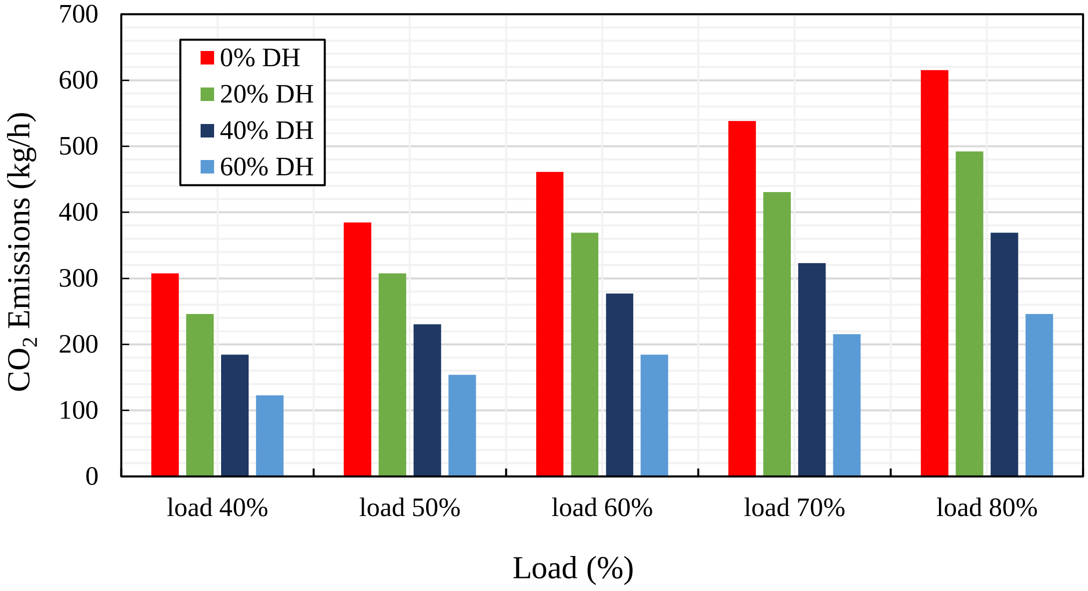

Figure III.6: Effect of dual fuel and engine load on CO_2 emission.

The variation of CO_2 emission is shown in Figure III.6. The CO_2 emission of pure diesel and dual fuel blend was found to increase with the increasing of hydrogen addition. At all load conditions, the CO_2 emissions of dual fuel blend were lower than that of the pure diesel. The reduction of CO_2 emission for hydrogen/diesel (20/80) dual fuel blend was found to be 61.51 Kg/h, 92.27 Kg/h and 123.03 Kg/h at load of 40%, 60% and full load 80% respectively as compared to the emission of pure diesel fuel. Therefore, results show better combustion of fuel as compared to the pure diesel fuel.

4.4. Oxides of nitrogen emission

Oxides of nitrogen; nitric oxide (NO) is formed from the combination of nitrogen and oxygen present in the intake air under the high-temperature conditions that result from the combustion process. As the gas temperature drops during the expansion stroke, the reaction is frozen. In the presence of additional oxygen in the air, some NO transforms to nitrogen dioxide (NO_2), a toxic gas. The NO and NO_2 combined are referred to as oxides of nitrogen or NO_x. [37]. Figure III.7 shows the results obtained of the dual fuel engine on NO_x emissions.

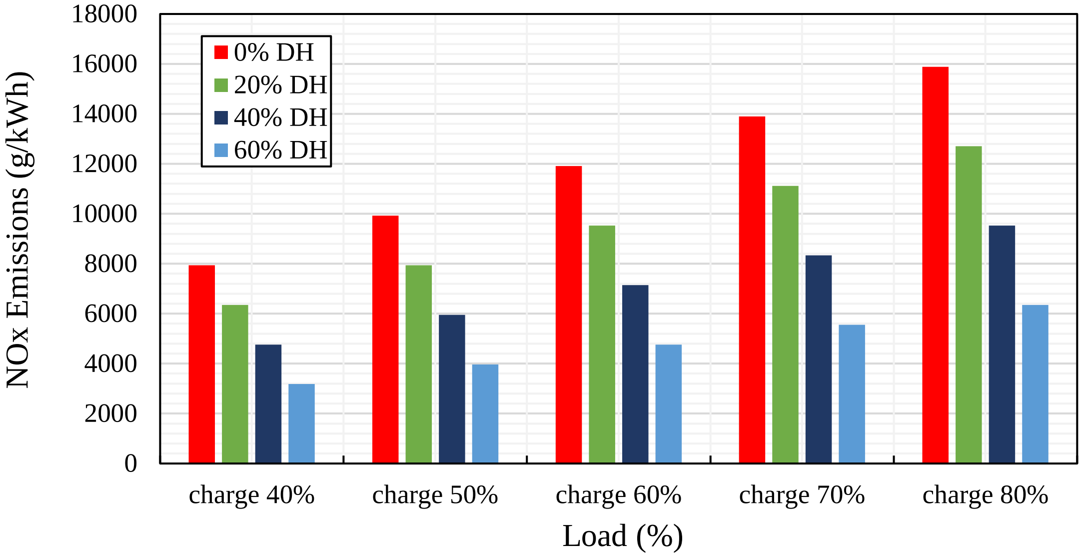

Figure III.7: Effect of dual fuel and engine load on NO_x emission.

Figure III.7 shows the variation of NO_x emission with engine load. The NO_x concentration decreases with the increase of engine load for all the fuels. Compared with diesel, NO_x emission of the dual fuel decreases slightly up to 1588.57 g/kWh, 2382.85 g/kWh and 3177.13 gkW/h at all 40%, 60% and 80% engine load, respectively, condition with 20% of hydrogen addition.

Although the combustion of hydrogen with oxygen produces water as its only product; other experimental researches indicated that the combustion of hydrogen with air can also produce oxides of nitrogen. The high temperature that developed inside the combustion chamber and lean mixture combustion promotes good thermal efficiency, also results in less emission of HC and CO but causes amounts of NO_x emission [1, 11].

5. Comparative analysis between LPG and H_2 addition in the internal engine

5.1. Comparative performance analysis

In the present study, a comparative analysis is carried out to evaluate the performance characteristics of CAT3512 diesel engine using 70% blend of hydrogen versus 70% of LPG blend [38] compared with fossil diesel under load of 80%.

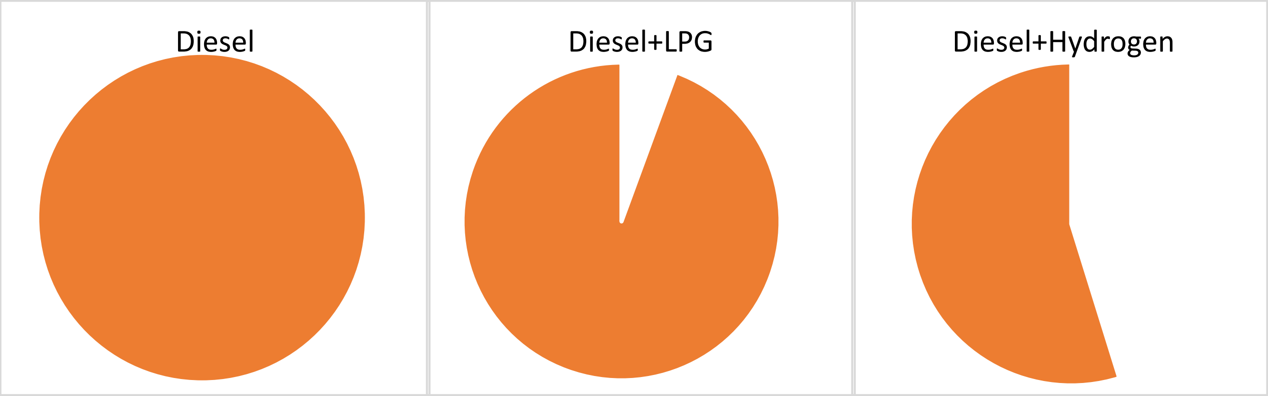

Figure III.8: Comparative analysis of the performance characteristics of CAT3512.

The above figure shows that the engine converted to dual-fuel mode can operate with a lower mass flow rate (LPG/diesel) or (Hydrogen/diesel) compared to that of the original diesel engine. We notice a decrease in fuel consumption of the dual-fuel mode engine of 10.8% for LPG and 87.07 % for hydrogen. The reduction in mass flow consumption due to the lower heating value (LHV) of LPG and hydrogen, which is higher than that of pure diesel. In addition, the variation of energy kept the same energy of the engine for both (Hydrogen/diesel) blend or for (LPG/Diesel) blend which is equivalent to 2127.21 kWh.

5.2. Comparative emission analysis

A comparative analysis is carried out to evaluate the emissions characteristics. As shown in Table III.5 a comparison of the variation in CO_2, CO, NO_x and HC emission of hydrogen from our results versus another work that uses LPG as an alternative fuel [38] at 80% loading condition.

Table III.5: Comparison effect of dual fuel engine on CO_2, CO, NOx and HC emission.

	CO_2 (Kg/h)	CO (g/KWh)	NO_X (gKW/h)	HC (g/kw)
Diesel	576.384	8508	14889	2339.7
Diesel+LPG	551.17	2956.61	5113.5	718.18
Diesel+hydrogen	172.9152	2551.7	4465.475	701.7175

At 80% load condition and 70% addition of hydrogen or LPG blend, the CO2 emissions of dual fuel blend were lower than that of the pure diesel. The reduction of CO2 emission for hydrogen addition was found to be 70% lower than that of pure diesel and by 4.4% for LPG. In addition, the table clearly shows that CO2 emission is lower 65.6% in hydrogen fuel compared to the LPG. Therefore, results show better combustion of fuel as compared to the pure diesel fuel especially for hydrogen/diesel dual fuel blend.

Carbon monoxide in the exhaust gas is resulted by incomplete combustion in the combustion chamber. For the engine run in pure diesel mode, the CO number is relatively higher than the engine run in dual-fuel mode by 70% for hydrogen and by 65.3% for LPG. In addition, the table clearly shows that CO is lower 4.7% in hydrogen fuel compared to the LPG. The reason for lower CO emission in hydrogen addition is due to absence of carbon atoms in the hydrogen structure.

Nitrogen oxides has adverse health effects, long-term exposure may impair lung function and increase the risk of respiratory disorders. These oxides are products of oxidation of atmospheric nitrogen in the combustion chamber. It can be seen from Table III.5 that the NO_x emission for hydrogen is lower than that of pure diesel by 70% and by 65.66% for LPG. Nevertheless, other researches find out that the high temperature, which occurs during the combustion process produce amounts of NO_x emission.

Combustion process in the combustion chamber results unburned hydrocarbons in the exhaust gas. As shown in Table III.5, for CAT3512 engine run in pure diesel mode, HC number in the exhaust gas is higher compared to dual fuel mode by 70% for hydrogen and by 71% LPG. For the CAT3512 engine run in dual-fuel mode, HC number decreases significantly. The table III.5 shows that HC number in the exhaust gas varies for hydrogen is higher by 4% compared to the LPG.

6. Technical-economic analysis for hydrogen production

Among numerous applications for the hydrogen production without harmful emissions, hydrogen production from renewable energies is a key part in the energy transition to realize a sustainable energy economy for both developed and developing nations. This study is conducted to estimate the potential of hydrogen production driven by solar energy. This section is composed mainly of two subsections; one for the production of renewable hydrogen from solar photovoltaic system by water electrolysis process. The second part of this section is for cost estimation of hydrogen production system. The caterpillar is the only source of energy for oil companies in isolated drilling areas in Algeria. In our study, we chose the 'Drilling & Work Over Company, ENTP', Which is assigned to drilling at medium and large depths, the drilling and maintenance of hydrocarbon wells (Work-Over) also the drilling of deep water wells. ENTP has a fleet of 67 devices, which are classified in the table below:

Table III.6: ENTP drilling equipment park 2016 [39].

Devices Type	500HP	750HP	1000HP	1200HP	1500HP	2000HP
Number	3	6	1	11	30	16

6.1. Technical analysis

The dimensioning of photovoltaic installation amounts to determine the necessary area of the photovoltaic generator to adopt a photovoltaic system sufficient to cover the needs of the electrolyser used at all times. The first step to evaluate the hydrogen production using photovoltaic panels is to analyze the solar potential in Algeria particularly in Hassi Messaoud. For this, the solar irradiation of the chosen site is needed. Once the solar irradiation incident and the necessary electrical energy requirements of the electrolyser is known, the surface of the photovoltaic generator can be calculated.

6.1.1. Site selection

The estimation of the solar power available on a given site is probably the most significant stage; the various solar irradiation of the selected site of our study (Hassi Messaoud) from 2004 to 2014 is illustrated in Table III.7:

Table III.7: Global Horizontal Irradiation of Hassi Messaoud [40].

Year	GHI (kWh/m²)
2004	2201
2005	2183
2006	2031
2007	2040
2008	2056
2009	2114
2010	2136
2011	2174
2012	2106
2013	1987
2014	1937
Average	2147

6.1.2. System description

Photovoltaic panels generate electricity directly from sunlight via an electronic process that occurs naturally in certain types of material, called semiconductors. Electrons in these materials are freed by solar energy and can be induced to travel through an electrical circuit, Powering electrical devices [9]. The generated electric by the renewable source will be sent to the electrolyser to drive the electrolysis process of water to produce hydrogen. After that the hydrogen produced will be sent to the diesel engine with a blend of diesel fuel wich is known as dual-fuel technology, as presented in Figure III.9. For this study, an alkaline type electrolyser was used. It has a high return, a long life cycle and a good aptitude for renewable energy systems [41]

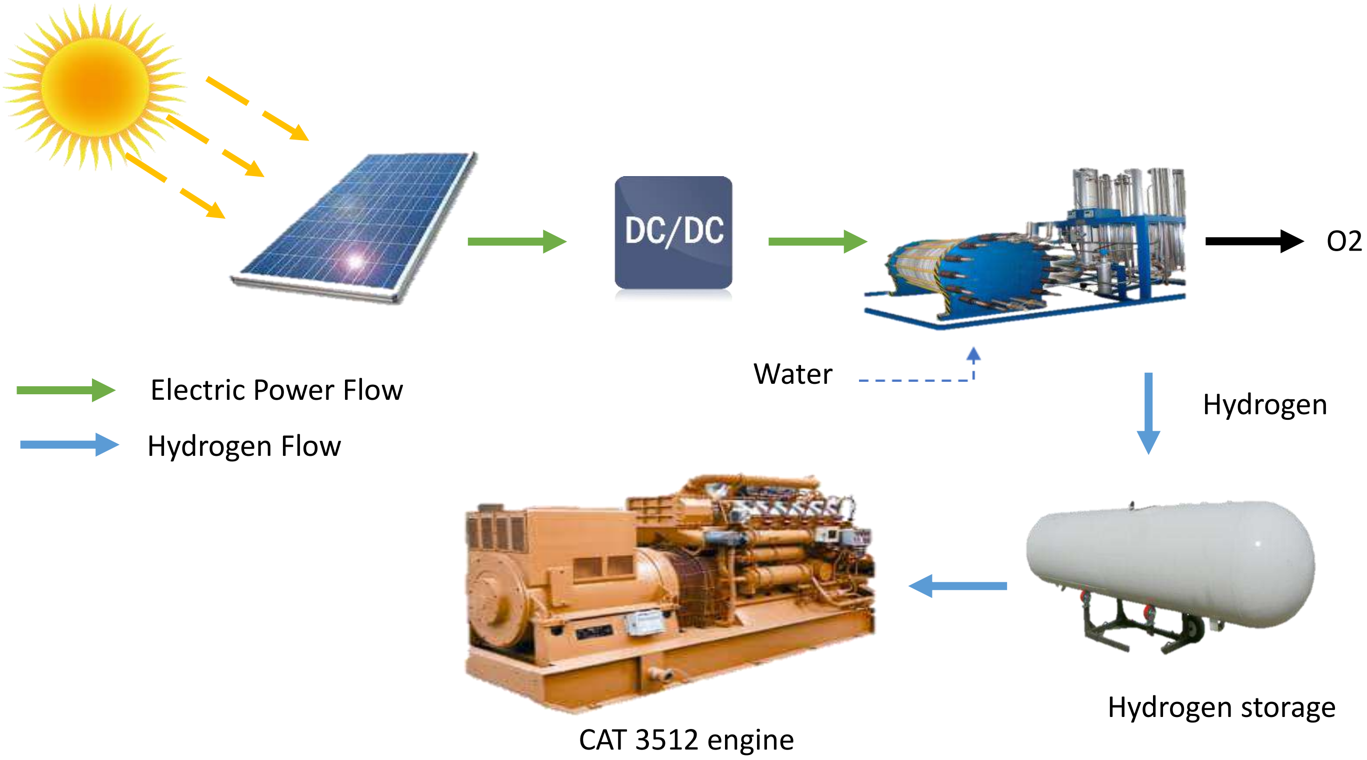

Figure III.9: Basic diagram of the hydrogen production plant.

6.1.3. Installation dimensioning (REn/H_2)

6.1.3.1. Energy dimensioning of the electrolyser

Once the annual hydrogen production capacity is known, we can deduce the necessary electrical energy needs of the electrolyser. In order to estimate the maximum energy that the electrolyser is able to absorb during the year, the following equation is used [42]:

$$E_{el} = \frac{K_{el,th}\, m_{H_2}}{\eta_{elec}} \qquad (9)$$

E_{el}	Energy absorbed by the electrolyser, kWh/year.
$K_{el,th}$	Theoretical electrolytic power consumption, kWh/kg.
m_{H_2}	Annual hydrogen production, kg/year.

In this study, we used 32 alkaline electrolyzer model, its electrical consumption equal to 108 kW [43]. Table III.8 shows the different capacities used, the electrical energy absorbed by the electrolyser and the number of electrolysers (stacks).

Table III.8: Dimensioning of the industrial electrolyser of the selected alkaline technology.

$load$	40%	50%	60%	70%	80%
m_{H_2} **(t/year)**	4000	5000	5990	6990	7990
E_{el} **(GWh/year)**	280	350	419	489	559

The dimensioning of the industrial electrolyser of the selected alkaline technology is illustrated in the table above. The focus of this subsection was to observe the electrolysis performance in the volume of hydrogen produced and the electrical energy absorbed by the electrolyser. As shown in table III.8 the higher consumption of hydrogen is needed, the higher electrical energy absorbed is needed.

6.1.3.2. Dimensioning of photovoltaic production

Since the electrical characteristics of photovoltaic cells depend on weather conditions, the energy model chosen must take these considerations into account. Here, we will use a polynomial model to deduce the energy that can be obtained as a function of the incident radiated power per unit area and the cell temperature of the panels [44]. This model is easily identifiable from the manufacturer documents. The production of hydrogen by the electrolyser requires that the photovoltaic generator provide an annual quantity of energy estimated by:

$$E_{PV} = {}^{E_{el}}\!/_{\eta_{elec}\,\eta_p} \qquad (10)$$

Where:

E_{el}	Energy absorbed by the electrolyser, kWh/year.
η_{el}	Electrolyzer efficiency, %.
η_p	Additional efficiency included to account for energy losses in the electrolyser, %.
E_{PV}	Electrical energy delivered by the renewable source, kWh/year.

After that, we calculate the land area that would be required for a solar photovoltaic power plant for electrical power delivering that we need, In order to estimate the surface area formula (11) is used.

$$A_{PV} = {}^{E_{PV}}\!/_{\eta_{PV}\,GHI} \qquad (11)$$

Where:

E_{PV}	Photovoltaic energy, kWh.
η_{PV}	Photovoltaic generator efficiency, %.
A_{PV}	Total area of photovoltaic generator, m².
GHI	Global solar irradiation on a horizontal plane, kWh/m².

The dimensioning of a photovoltaic installation amounts to estimate the necessary area of the photovoltaic generator to adopt a photovoltaic system sufficient to cover the needs of the electrolyser used at all times. Once the global solar irradiation incident on the generator plane and the necessary electrical energy requirements of the electrolyser is known, the area of the photovoltaic generator can be calculated.

In this study we used crystalline silicon photovoltaic panel with a power of 250W at peak, and an efficiency of 15.28% [45]. The results we obtained are illustrated in Table 9:

Table III.9: Dimensioning of photovoltaic generator.

m_{H_2} (t/year)	4000	5000	5999	6990	7990
$E_{pv}(MWh/year)$	373	467	559	652	746
A_{PV} (km²)	1.9	1.49	1.79	2.08	2.38

As we can see from the table above, there is a proportionate relationship between the ratio capacities of hydrogen production and the photovoltaic generator area, as shown in the table the photovoltaic generator area increases with the increasing of hydrogen production capacity.

6.2. Economic study

The second part of the study is the economic evaluation of the system. Generally, the approach used to assess the economic interest of an energy system is based on a fixed operating scheme. In the case of a photovoltaic system, in order to calculate the cost of the electricity produced. A life cycle cost analysis (LCC) takes into account investments cost, including capital investment costs, as well as the installation costs; future costs, including energy costs, operating costs, maintenance costs, capital replacement costs; and any resale, salvage, or disposal cost, over the life-time of the project [46].

6.2.1. Total investment cost

The total cost of a photovoltaic installation consists of two distinct parts [47]:

6.2.1.1. Initial investment (I_0)

The initial investment (I_0) includes the cost of the installation of PV system, which could be divided into:

C_{PV}	The capital cost of photovoltaic modules;
C_{BOS}	BOS (balance of system) cost that includes all parts of the PV system except the PV module itself (for example, wiring, racking, and other system installation costs).

To estimate the initial investment (I_0), the following equation is used:

$$I_0 = C_{PV} + C_{BOS} \tag{12}$$

6.2.1.2. Operation and maintenance costs

The cost of operation and maintenance (O&M) represents all actual cash operation and the expenses incurred to maintain a system. For a photovoltaic system, O&M costs are essentially [48]:

- Periodic monitoring ;
- Periodic maintenance of system components.

6.2.2. Levelized Cost of Electricity (LCOE)

The cost of electricity produced by the PV solar system is calculated based on several factors, using the method known as the LCOE. Which is an analytical tool that can be used to compare alternative technologies when different scales of operation, investment or operating periods exist. The levelized cost of electricity is the net present value of total life cycle costs of the project divided by the quantity of energy produced over the system life. The PV LCOE, expressed in \$/MWh, can be defined by the following formula [49]:

$$LCOE = \frac{I_0 + \sum_{n=1}^{N} (C_{O\&M} + C_r)/(1+r)^n}{\sum_{n=1}^{N} E_{el,year} (1-\deg)^n/(1+r)^n} \tag{13}$$

Where:

I_0	Initial investment cost, \$
N	System life, years
$C_{(O\&M)}$	Maintenance and operating costs, \$

C_r	Replacement cost, $,
r	Discount rate, $
E_{el}	Annual electricity production, kWh/year
deg	Degradation rate, %

The fall in electricity costs from utility-scale solar photovoltaic (PV) since 2010 has been remarkable. According to the forecasts of the International Renewable Energy Agency (IREA). They indicated that solar PV costs now half of what they were in 2010 driven by an 81% decrease in solar PV module prices since the end of 2009, along with reductions in balance of system (BOS) costs, the global weighted average LCOE of utility-scale solar PV fell 73% between 2010 and 2017, to USD 0.10/kWh. This reduction could fall by another 60% over the next decade [50].

It is assumed that for our photovoltaic system, the duration of the components will be equal to the operating life. Therefore, the cost of replacing the components is negligible. In order to complete the study, we have relied on the PV panels mentioned above which are characterized by the market values listed in the table below:

Table III.10: Characteristic of the PV used technology [51].

Characteristic	Value
Lifetime (year)	30
Discount rate (%)	6
Efficiency (%)	15
Degradation rate (%)	-0.4
Module unit cost ($/m²)	115.6

In order to estimate the total cost of the PV installation of the solar photovoltaic hydrogen production, we used the equations indicated above, a calculation program written in Matlab software was developed. For a lifetime of 30 years for each system, a discount rate of 6%. The calculation results are shown in the following table.

Table III.11: Techno-economic electrolysis study for different capacities.

Load	40%	50%	60%	70%	80%
$\dot{m}_{H_2}$(t/year)	4	5	5.99	6.99	7.99
Cm_{pv} (M$/year)	1.12	1.4	1.68	1.96	2.24
C_{pv}(M$)	243	304	364	425	486
C_{H_2} ($/kg)	6.2824	6.2824	6.2824	6.2824	6.2824
C_{TI} (M$/year)	291	363	435	508	580
LCOE ($/kWh)	0.0603	0.0603	0.0603	0.0603	0.0603

The change in total cost as a function of the hydrogen production for different capacities values shown in Table (III.11). Indicates: for each increase in hydrogen capacity offset by an increase in photovoltaic field surface leads to an increase in the total cost of photovoltaic system investment (costs of initial investment cost and maintenance), and increases the production of electric power.

7. Conclusion

In the first part of this chapter, we presented the influence of the dual-fuel operation on the engine operating parameters at different engine loads. The results show that the engine converted to dual-fuel mode can operate with the same efficiency compared to normal diesel. Then we studied the influence of this technology on the emission characteristics of a Caterpillar engine converted to dual fuel mode. The results show that there is a significant reduction in greenhouse gases such as CO_2 and other pollutants emitted by the diesel engine.

In the second part of the study, we focused on the energy dimensioning of the hydrogen production installation. Finally, we briefly described the methods used to estimate the total discounted cost of hydrogen and the cost of electrolyser, which is composed of three costs: initial investment that depends on the installed capacity, the cost of maintenance and operation and the cost of replacement. We estimated the cost of electrolytic hydrogen production in the region of Hassi Messaoud for the ENTP Company. We have also presented a comparison of the cost of kilogram of hydrogen produced with different capacities, the results show that for a production capacity of 4 (t/year) the hydrogen cost of the PV / H_2 plant, is the least expensive (291 M$ / kg of H_2).

General conclusion

General conclusion

Conventional fossil fuels have been used for industrial power facilities for long time, but the decline of available fossil fuels and awareness of the environmental consequences drives the exploration of alternative energies. Alternative fuels provide ways to shift energy consumption to low pollution and more energy diversity. In this context, green hydrogen obtained from renewable electricity is seen as a promising energy carrier for the future.

The objective of this study is to investigate the combustion, performance and emission characteristics of Caterpillar3512 diesel engine converted into dual-fuel mode using hydrogen as an alternative fuel. The following are the conclusion from the results obtained after investigations of Caterpillar3512 diesel engine powered by dual fuel using different substitutions of hydrogen. The results obtained are compared with diesel fuel.

- For dual fuel operation, as hydrogen is injected with diesel fuel, there was a persistent trend of reduction of Specific Fuel Consumption (SFC) with increase in load for given hydrogen injection. This is an indicative of the enhanced combustion of conventional diesel combustion because of high flame velocities and high calorific content of the participating hydrogen with air resulting in complete combustion of fuel and due to the lower heating value (LHV) of hydrogen is higher than that of diesel
- For dual fuel operation, CO and HC emissions are significantly lower than those of the original diesel engine were. It has been observed that the CO formation for hydrogen/diesel (20/80) dual fuel blend reduces by at full load 80% as compared to the emission of diesel fuel alone. In addition, at high load the HC formation reduces by 499.26 g/kWh when compared to diesel condition with 20% of hydrogen addition. This reduction is due to the increase in combustion temperature associated with higher engine load.
- CO_2 formation were almost negligible as expected, it can be generally deduced that CO_2 emissions reduced as proportions of hydrogen in diesel increased. At full load, the reduction of CO_2 emission for hydrogen/diesel (20/80) dual fuel blend was found to be 123.03 Kg/h compared to the emission of pure diesel fuel. Therefore, results show better combustion of fuel as compared to the pure diesel fuel. The NO_x concentration also shows a decrease with the increase of hydrogen fractions in the blends of diesel.

Condition with 20% of hydrogen addition the formation of NO_x decreases slightly up to 3177.13 gkW/h at full load (80%).

- The comparative analysis of the results we obtained with another work that used LPG as alternative fuel shows that the engine kept the same energy on the engine for both ((Hydrogen/diesel) blend or for (LPG/Diesel) blend. We also shows that the use of gaseous hydrogen and LPG in diesel engine greatly reduced the pollutant emissions. Corresponding to the results we obtained CO, HC and NO_x emissions were lower for hydrogen fuel by 70% than diesel. Compared hydrogen to LPG fuel the reduction of these emissions were not so visible, almost the same reduction ratio were found. In case of CO_2 emissions, differences were significant for hydrogen, CO_2 emissions were lower compared to diesel by 70% and for LPG by 68.62%.

The second part of the work was a technical-economic study for the massive hydrogen production by the water electrolysis process using solar energy via photovoltaic system. In order to achieve this goal, we first started of hydrogen production dimensioning using renewable energies in Algeria particularly in Hassi Messaoud. The design of the REn / H_2 installations (and consequently the cost of producing electrical energy) has been accomplished according to the annual hydrogen production capacities imposed. The dimensioning allowed us to define the size of each component constituting the installation. An economic optimization of the several different configurations for the same system has been carried out, in order to obtain a system optimized for the cost. The mathematical models are grouped in a calculation code written in Matlab software in order to assess the electrical production potential.

- The results shows that the evaluation of the solar electricity production in Hassi Messaoud, shows high potentials of solar energy exploitation widely observed with a power generation that exceeds the 2147 kWh/m² yearly a large scale hydrogen production from solar energy is largely possible. We also conclude that for a small production capacity of 4 (t/year) the PV / H2 installation gives a better electrical cost by comparing with other production capacity (291 M$ / kg of H_2). The results confirm that a key parameter to reduce the cost of hydrogen production is the cost of electricity (which contributed more than 80% to the cost of hydrogen production), logically for a process of electrolysis of water.

It can be concluded that generally, hydrogen will provide a viable alternative fuel to the fast depleting fossil fuels in the future, but investigators must be fully aware of the challenge ahead in particular concerning the global environmental effect.

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Annex I: Matlab Code – Experimental data averaging

```
%--------------------------------------%
% Energy absorbed by the electrolyser %
%--------------------------------------%
fprintf('Annual hydrogen production(kg/year)\n')
mH2=7.99*1e+6     %(kg/year)
Kelth=52.5;       %Theoretical electrolytic power
consumption(kWh/kg)
rendel=0.75;    %Electrolyser efficiency(%)
fprintf('Energy absorbed by the electrolyser(kwh/year)\n')
Eel=(mH2*Kelth)/rendel    %(kWh/year)
%--------------------------------------%
%         Photovoltaic energy         %
%--------------------------------------%
rendp=1;%Additional efficiency included to account for
energy losses in the electrolyser (%)
fprintf('Photovoltaic energy (kWh/year)\n')
Epv=Eel/(rendel*rendp)    %(kWh/year)
%---------------------------------------%
% Total area of photovoltaic generator %
%---------------------------------------%
rendpv=0.15 ;  %Photovoltaic generator efficiency(%)
GHI=2087.73;   %Global Horizontal solar irradiation on an
inclined plane(kWh/m²/year)
fprintf(' Total area of photovoltaic generator (m²)\n')
Apv=Epv/(rendpv*GHI)  %(m²)
%---------------------------------------%
%    Photovoltaic electricity cost     %
%---------------------------------------%
N=30;                 %Lifetime(year)
r=6/100;              %Discount rate(%)
```

```
f=3.5/100;          %Inflation rate(%)
d=0.004;            %Degradation rate(%)
Cmod=689*(1-0.83); %PV module cost($/m²)
Cpv=Cmod*Apv ;     %PV investment cost($)
Cbos=0.5*Cpv;      %Cost of Balance Of System(50%)
fprintf('PV system investment cost,$\n')
I0=(Cpv+Cbos)      %($)
fprintf('Maintenance and operating costs($)\n')
COM=0.004*Eel;     %($)
Cr=0;               %PV replacement cost($)
P=(COM/(f-r))*((((1+f)/(1+r))^N)-1);
A=(P+I0)*((r*((1+r)^N))/(((1+r)^N)-1));
fprintf('Cost of life cycle,$/kWh\n')
LCOE=A/Eel          % ($/kWh)
fprintf('Total cost of PV system,$\n')
CTpv=I0+(COM*N)     %($)
%---------------------------------------%
%   Total cost of PV/H2 installation   %
%---------------------------------------%
TF=7;      % Operating time of the electrolyser(year)
f=11/24;     % Capacity factor
HIV=39.4;     % Higher Heating Value (kWh/kg)
QH2max=(mH2/(365*24))*11.126*(1/f);%(Nm3/h)
Kout=3.5418*QH2max;           %(kW)
rendutil=HIV/(Kelth/rendel);%Useful efficiency of electrolyser
Cel=368;                    %Unit cost of electrolyser($/kW)
Ciel=(Kout/rendutil)*Cel; %Investment cost of electrolyser($)
Cmel=(2/100)*Ciel   ; %Maintenance cost of electrolyser($)
Crel=(25/100)*Ciel ;       %Replacement cost of electrolyser($)
fprintf('Total cost of electrolysis,($)\n')
Cieltot=Ciel+Crel+(Cmel*N)    %($)
```

```
fprintf('Total cost of PV/H2 installation,$\n')
CTI=CTpv+Cieltot
cm=COM+Cmel+Crel;
ctot=(I0+Ciel);
ssom=0;
for n=1:1:N
    CCC=cm/((1+r)^n);
    ssom=ssom+CCC;
end
CCCC=ctot+ssom;
ttom=0;
for n=1:1:N
    BB=mH2/((1+r)^n);
    ttom=ttom+BB;
end
FF=ttom;
fprintf('Hydrogen cost,$/kg\n')
CH2=CCCC/FF
```