Underground Geological Sequestration of Carbon Dioxide (CO_2) and its Effect on Possible Enhanced Oil Recovery (EOR) in Fractured Reservoir

By

Anaiz Gul Fareed

Reg # 00000119937

Session 2015-17

Supervised by

Dr. Asif Hussain Khoja

A Thesis Submitted to the US-Pakistan Centre for Advanced Studies in Energy in partial fulfilment of the requirement for the degree of

MASTER of SCIENCE in

ENERGY SYSTEMS ENGINEERING

US-Pakistan Centre for Advanced Studies in Energy (USPCAS-E)

National University of Sciences & Technology (NUST)

H-12, Islamabad 44000, Pakistan

July-2019

THESIS ACCEPTANCE CERTIFICATE

It is certified that final copy of MS/MPhil thesis written by Mr. **Anaiz Gul Fareed** (Registration no. **00000119937)** of **U.S. – Pakistan Centre for Advanced Studies in Energy** has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is free of plagiarism, errors and mistakes and is accepted as partial fulfilment for award of MS degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature: ___________________

Name of Supervisor: Dr. Asif Hussain Khoja

Date ___________________

Signature (HoD): Dr. Naseem Iqbal

Date: ___________________

Signature (Dean/Principal): Prof. Dr. Zuhair S. Khan

Date: ___________________

Certificate

This is to certify that the work in this thesis has been carried out by **Mr. Anaiz Gul Fareed** and completed under my supervision at USPCAS-E, NUST, Main Campus, Sector H-12, Islamabad, Pakistan.

Supervisor ____________________

Dr. Asif Hussain Khoja
USPCAS-E
NUST, Islamabad

GEC Member # 1 ____________________

Dr. Naseem Iqbal
USPCAS-E
NUST, Islamabad

GEC Member # 2 ____________________

Dr. Muhammad Bilal Sajid
USPCAS-E
NUST, Islamabad

GEC Member # 3 ____________________

Mian Muhammad Akram
Chief Reservoir Engineer
OGDCL, Islamabad

HoD ESE ____________________

Dr. Naseem Iqbal
USPCAS-E
NUST, Islamabad

Principal USPCAS-E ____________________

Dr. Zuhair S. Khan
USPCAS-E
NUST, Islamabad

Dedicated to my Parents without whom nothing in this world would have been possible.

Acknowledgements

All the praises to Almighty Allah the greatest of all, I am indebted to my supervisor Dr. Asif Hussain Khoja for providing me time and support in completion of my thesis in very critical time. In addition to, I am extending my gratitude to my GEC members, Dr. Naseem Iqbal (HoD ESE), Dr. Muhammad Bilal Sajid (TEE Department) for their feedback and support as well.

I would like to express my gratitude to my co-supervisor Mr. Mian Muhammad Akram (Chief Reservoir Engineer OGDCL) for his gracious support and deep technical insights of this research. I also appreciate Reservoir Engineering Team of OGDCL for their support and allowing me to do research on one of their core fields and helping me with learning of tools and methods required for this research.

I thank Dr. Muhammad Zubair for his invaluable support to me during my research. I also appreciate the support of teaching and non-teaching faculty of U.S. Pakistan Centre for Advanced Studies in Energy for all the things that facilitated me during my research.

Abstract

Due to concerns over rising emissions from carbon dioxide (CO_2), from fossil fuel utilization, there has been a strong emphasis on the development of a safe, economical, practical method of carbon capture utilization and storage (CCUS). CO_2 is a considered as major threat for rapid environmental uncertainties. This tremendous amount of CO_2 emissions also produces in Pakistan, and Pakistan as signatory of (COP21) has also pledged to decrease carbon footprint. One way for reduction of these CO_2 emissions is underground geological sequestration in depleted oil field or exhausted reservoirs. CO_2 sequestration in oil reservoirs is proven technology, these reservoirs not only offers potential of high storage of CO_2 but this technique could also target the large amount of conventional and heavy oil which remain in reservoirs worldwide after conventional methods have been exhausted through a technique called enhanced oil recovery (EOR). In this study, numerical reservoir simulation is conducted using Eclipse Reservoir Simulator. The site selected for underground geological sequestration of CO_2 emissions is depleted oil field of Pakistan having fractured reservoir with very high permeability. In this case, reservoir base case model with only water flooding in its previous history was compared with reservoir model established for underground geological storage of CO_2 through three different injection rates, the main objective of this research is to evaluate storage potential of CO_2 emissions in depleted oil field while also investigate the effect of CO_2 injection on reservoir maintenance, additional oil recovery, and additional gas recovery of same field. The simulation result show site selected for CO_2 injection has the potential to store more than 9 billion cubic feet (BCF) of CO_2 emissions in each case, while also has the major effect on reservoir pressure maintenance, but improved in oil recovery was not observed due to deprived saturation of oil in oil bearing zones but it recovers additional marginal recovery of natural gas when compared to base case. The results of this study ought to help in preparing for future improvement in underground geological sequestration of CO_2 research.

Table of Contents

List of Figures

List of Tables

List of Publications

Conference Proceedings

- **"Simulation Study for Fractured Reservoir for Enhanced Oil Recovery (EOR)"**

  Anaiz Gul Fareed, Muhammad Zubair | 5th International Conference on Energy, Environment and Sustainable Development 2018 (EESD 2018)

  http://eesd.muet.edu.pk/wp-content/uploads/2019/03/Theme-03.pdf

- **"Economic Evaluation & Feasibility Research for Enhanced Oil Recovery (EOR) Research"**

  Anaiz Gul Fareed, Muhammad Zubair | 5th International Conference on Energy, Environment and Sustainable Development 2018 (EESD 2018)

List of Abbreviations

EOR	Enhanced Oil Recovery
CO_2	Carbon Dioxide
OOIP	Oil Initially in Place
COP	Conference of Parties
CCS	Carbon Capture and Storage
MBE	Material Balance Equation
MMP	Minimum Miscible Pressure
MM Ton	Million Metric Ton
API	American Petroleum Institute
WAG	Water Alternating Gas
LPG	Liquified Petroleum Gas
SWAG	Simultaneous Water Alternative Gas
NPV	Net Present Value
BTU	British Thermal Units
PVT	Pressure Volume and Temperature
Bbls/day	Barrels per Day
E & P	Exploration and Production
P_b	Bubble Point Pressure
RTKB	Rotary Table Kelly Bushing
MM STB	Million Stock Tank Barrel
GIP	Gas in Place
MM SCF	Million Standard Cubic Feet
BCF	Billion Cubic Feet

Chapter 1

Introduction

This chapter gives a brief overview, background, and purpose of the study, stating Pakistan energy outlook, its current trends, underground geological sequestration of carbon emissions, and also explaining role of enhanced oil recovery in improvement of oil recovery. Furthermore, this chapter also states the research problem and a possible solution.

1.1. Background

Pakistan has been facing an energy crisis for the past many years and the economy of Pakistan has confronted the increase in energy demand, which not only restrained economic growth but also the development of the country [1]. where particularly fossil fuels have greater contribution to primary energy consumption of Pakistan, but this immense use of fuels is also linked to increased greenhouse gases (GHG) and global warming in the country, which tends to make Pakistan as one of few countries vulnerable to climate change threat [2].

It is also true that global energy supply is seeing the shift towards renewable energy, and renewable technologies are emerging as best replacement to reduce dependency on fossil fuels, but still oil and gas will continue to be the world`s top two energy resources accounting for about 60 percent of global energy demand [3]. In this context, Pakistan faces a major climate challenge ahead, as country already faces with a 0.5 °C rise in temperature in the last 50 years [2] and despite rising trends towards alternate technologies, fossil fuel, in which particularly coal will be the major source of producing electricity in this country, as nine of the 17 China Pakistan Economic Corridor (CPEC) projects to be run on coal [4], and when we talk about increasing GHG emissions, coal is regarded as one of the primary sources to deteriorate the environment, but also, it is part of the core industries that contribute to the economic development of the country [5]. Hence despite the fact coal regarded as one of the major environmental threat, its use will not be challenged, and hence will be contributing to the rising CO_2 concentration in the atmosphere.

As far as mitigating the environmental threat of this country are concerned underground geological storage is considered one of the promising techniques to reduce CO_2 emissions from natural and industrial sources [6]. The core objective of this technique is to prevent CO_2 to be released into the atmosphere and store in the favorable geological sink for long. Geological storage of these emissions could be ocean, deep rocks, marked territories, brine or coal seams, but based on recent development and current technology the best suited sites for underground geological sequestration are abandoned deep oil and gas reservoirs, which offers great potential to store large amount of CO_2 emissions with minimum possible risks of leaks to the surface, though CO_2 is the non-flammable gas but still leaks assessment taken into consideration once CO_2 sequestrated and stored deep in geological formation. While there is always speculation for big cost of capturing and sequestration of CO_2 in geological formation, that's why it is always recommended approach in sequestration operation to make commercial use of CO_2 emissions when injected into depleted oil and gas reservoirs, and this commercial use could bring recovery of oil from those depleted fields in the form of Enhanced Oil Recovery (EOR).

EOR is the oil recovery technique where injection fluids are injected for additional recovery of oil, the fluids which are injected in EOR are sometimes not native to a reservoir and EOR aims to produce more favourable conditions in a reservoir so that a significant portion of residual oil been displaced for production [7]. Almost all processes of EOR especially miscible injection methods using CO_2 as injection fluid has been tested commercial scales and implemented in many depleted fields in past decades worldwide.

1.2. Problem Statement

Increase in energy demand in Pakistan has also resulted in an increase in carbon emissions from fossil fuel power plants, studies suggest CO_2 emissions could possibly reach to 278 MT in the year 2035 in Pakistan, making it more complex in tackling the threat of climate change, such environment not only currently affecting biodiversity of the country but also resulted in loss of over US$ 9.6 billion to the economy of Pakistan since 2010 [8]. The continuous emissions produced in the country from different industrial sources can be captured and sequestrated for underground geological storage in abandoned and exhausted oil fields of the country, these emissions when injected in these fields not only get stored for long, but can also produce additional recovery of oil from those fields via EOR. Total storage capacity in different oil and gas fields in

Pakistan estimated to be 1.7 Gt CO_2 [9]. CO_2 sequestration could also be targeted for coal mines, but most of the coal mines in Pakistan have shallow depth hence making these sites vulnerable to CO_2 leaks to the surface. On the other side Pakistan oil production to date has been characterized by small pocket reservoirs, which tend to go natural depletion after producing for some years during its natural recovery, throughout this natural recovery operator companies make screening and design strategy to get additional oil recovery from these reservoirs but failed to implement any EOR approach for additional oil recovery in this country [10]. The need for adapting EOR technologies has become inevitable for Pakistan because of the fact that the average recovery of hydrocarbon resources with its current pace could not meet the energy supply of the country.

While all different environmental agencies worldwide making sure to limit global temperature rise to 2 ℃ and by looking current rising emissions in the country, underground geological sequestration of CO_2 emissions could play a major role in limiting carbon emission in the atmosphere and possible success of the recovery of oil.

1.3. Research Hypothesis

Safe storage of CO_2 emissions through injection technologies is not a new phenomenon and has been practiced in the past decades. There are many options of injecting different sort of gases for additional oil recovery but CO_2 has some distinct properties which are more advantageous for any reservoir recovery [11]. There are two valuable characteristics of CO_2 for using this gas as injecting fluid, such as it is miscible with crude oil, and also it is cheaper than other fluids available as injection fluids [12]. This gas also has a higher solubility in crude oil when injecting at pressures of 700 psi, and dramatically reduced oil viscosity which makes the oil easier to flow at the surface. It also has low critical temperature and pressure and has properties similar to liquid as a dense phase while injecting CO_2 gas as supercritical fluid [13]. There are mainly two objectives to use CO_2 for EOR operations: as a fluid which is immiscible and does not mix with oil completely or as miscible fluid which is completely soluble with oil, CO_2-EOR operations with miscible flooding are of great success, because in miscible flooding CO_2 mixes with light hydrocarbons of oil and it becomes mutually soluble with residual and can trap oil effectively. Miscible flooding gives more productive results when CO_2 is more compressed (high density) and oil volume contains lighter hydrocarbons [12].

Underground geological storage of CO_2 is a proven technology and mentioned in published literature since the 1920s, industry professionals started to adapt hydrocarbon source (i.e. natural gas, LPG) of miscible injection for additional recovery of oil, but due to the fact that both these sources have low density, low viscosity, and hydrocarbon composition they were soon regarded as expensive and unsuitable for further use [14]. Ritchie field was the first pilot project which started CO_2 injection in 1964, CO_2 injection gained more fame when it was used in the Permian Basin for the SACROC unit in 1972 [15]. In the late 1990s, worldwide CO_2-EOR production of oil averaged more than 200,000 bbl/d with the amount from 79 individual projects, with huge production of oil comes from the United States alone at that time. Since its first use more than 100 CO_2-EOR projects been commenced by oil and gas industry professionals, CO_2 flooding successfully have been using in several areas of US, and also in other countries like in Turkey, Hungary, Canada, Trinidad, Brazil [16], [17].

1.4. Research Objectives

Following are the main objectives of this research work

- To investigate the underground geological storage of CO_2 emissions in the depleted oil field of Pakistan.
- To investigate the relationship of possible enhanced oil recovery (EOR) in the depleted oil field via injecting CO_2 with various injection rates.
- To study the effect of CO_2 injection on gas production rate, and reservoir pressure maintenance by implementing CO_2-EOR technique in base case reservoir of the selected site.

1.5. Scope of the Study

This research mainly focuses to study the storage potential of CO_2 in selected depleted field of Pakistan having a fractured reservoir and also to analyse the behaviour of CO_2 gas in the subsurface reservoir of same depleted field. This research comprises all the approach that is being used in the oil and gas industry. One of the major impacts that Pakistan is facing along with its energy crisis is greenhouse gas emissions of CO_2 gas and these gas emissions are increasing in the country along with the installation of other fossil fuel power plants for generation of electricity, hence underground geological sequestration of these CO_2 emissions became the objective of this research. The literature review part of this research comprises all the extensive research of underground geological sequestration of CO_2, what are the different injection technologies of CO_2, and the mechanism of CO_2-EOR adapted for the operation. In the methodology section of this research a site was selected to evaluate storage potential of CO_2 emissions, all the data available for injecting CO_2 in that field was characterized to develop a reservoir model using ECLIPSE reservoir simulator, that reservoir base case model was then compared to the model implemented with CO_2 injection technique, where CO_2 is injected with three different injection rates, and it was analysed how this CO_2 gas injection affect overall oil production rate, gas production rate, and reservoir pressure maintenance when compared to the base case model. The results are discussed and analysed while in the last chapter of this research conclusion remarks and future recommendation is given.

The Figure 1 demonstrates the organization of the study, showing methodology followed for this research work.

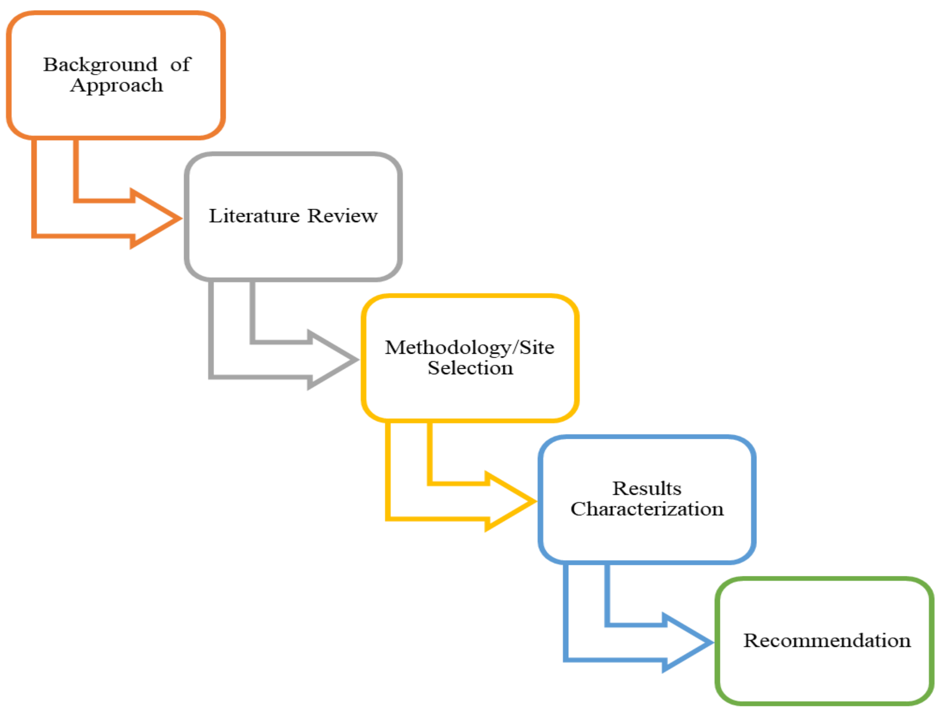

Figure 1 Organization of the Study

1.6. References

[1] B. S. R. of W. E. 2018 Energy, “67 th edition Contents is one of the most widely respected,” 2018.

[2] C. Qamar Uz Zaman, *Climate Change Profile of Pakistan (ASIAN DEVELOPMENT BANK)*. 2017.

[3] C. Name and C. Author, “PAKISTAN ECONOMIC SURVEY 2012-13,” 2012.

[4] AFP, “Nine of 17 CPEC power plants to be run on coal | The Express Tribune.” [Online]. Available: https://tribune.com.pk/story/1848007/2-nine-17-cpec-power-plants-run-coal/. [Accessed: 23-Jul-2019].

[5] R. K. Tiwary, “Environmental Impact of Coal Mining Onwater Regime and Its Management,” *Water. Air. Soil Pollut.*, no. 132, p. 185, 2001.

[6] M. Arif, M. Lebedev, A. Barifcani, and S. Iglauer, “Influence of shale-total organic content on CO_2 geo-storage potential,” *Geophys. Res. Lett.*, vol. 44, no. 17, pp. 8769–8775, 2017.

[7] G. P. W. Don W Green, *Book_Enhanced Oil Recovery Willhite.pdf*. 1998.

[8] B. Lin and M. Y. Raza, “Analysis of energy related CO_2 emissions in Pakistan,” *J. Clean. Prod.*, vol. 219, pp. 981–993, 2019.

[9] S. Holloway *et al.*, “An assessment of the CO_2 storage potential of the Indian subcontinent,” *Energy Procedia*, vol. 1, no. 1, pp. 2607–2613, 2009.

[10] M. A. Buriro and M. M. Hamza, “SPE 163124 Enhanced Oil Recovery : A Future For Pakistan,” 2012.

[11] Z. Ma, R. Pathegama Gamage, T. Rathnaweera, and L. Kong, “Review of application of molecular dynamic simulations in geological high-level radioactive waste disposal,” *Appl. Clay Sci.*, vol. 168, no. March, pp. 436–449, 2019.

[12] C. C. and A. C. F. C. D. Melzer, L. Stephen, "Carbon Dioxide Enhanced Oil Recovery," no. February, p. 18, 2012.

[13] W. L. Holm, "Evolution of the Carbon Dioxide Flooding Processes," *J. Pet. Technol.*, vol. 39, no. 11, pp. 1337–1342, 1987.

[14] M. Siwei, L. He, and Y. Qinghai, "Exploration and practice of carbon sequestration realized by CO_2 waterless fracturing," *Energy Procedia*, vol. 158, no. 2018, pp. 4586–4591, 2019.

[15] M. Seyyedi, P. Mahzari, and M. Sohrabi, "A comparative study of oil compositional variations during CO_2 and carbonated water injection scenarios for EOR," *J. Pet. Sci. Eng.*, vol. 164, no. August 2017, pp. 685–695, 2018.

[16] O. M. Mathiassen, "CO_2 as injection gas for enhanced oil recovery and estimation of the potential on the Norwegian continental shelf," *Nor. Univ. Sci. …*, no. May, 2003.

[17] E. Oil and R. Scoping, "Enhanced Oil Recovery Scoping Study," 1999.

Chapter 2

Literature Review

This chapter gives an extensive literature review of underground geological sequestration, options available for CO_2 sequestration, EOR, its classification, how CO_2-EOR is much prominent among other EOR technologies available for improved recovery. Reservoir properties are also briefed to give a clear idea that how these properties can be characterized for reservoir modelling.

2.1. CO_2 Emissions from Fossil Fuels

The main agenda of all the participating countries in Conference of Parties (COP21) was to limit global warming to below 2 ℃ with relative to pre industrial levels, to meeting this goal, it requires reduction of CO_2 emissions from fossil fuels power plants, which has become the major contributor of global warming [1]. In this global issue, many environmental agencies are busy addressing the permanent rising emissions of CO_2 and trying to achieve near zero emission target at the end of century, but this target cannot be achieved without limiting CO_2 emissions reduction from developing countries, which accounts for more than half of these worldwide global emissions, and these emissions are tend to be increasing faster, as many fossil fuels power plants are going to be implemented in coming years in these countries [2].

In country like Pakistan which is also a developing nation, and due to high population growth, the energy demand has been at rising pace in this country, and the considerable low prices of crude in recent years has also resulted in increase in demand of these fuels, and made renewable energy market less competitive in country. The Figure 2 depicts share of energy resources of Pakistan, where particularly fossil fuels have greater contribution to primary energy consumption in Pakistan energy generation mix [3]. By looking at the primary energy consumption, the majority of demand of the current primary energy consumption met by oil, natural gas, and coal. The country`s energy consumption was reported to be 38.8 MTOE in 2010-11 [4].

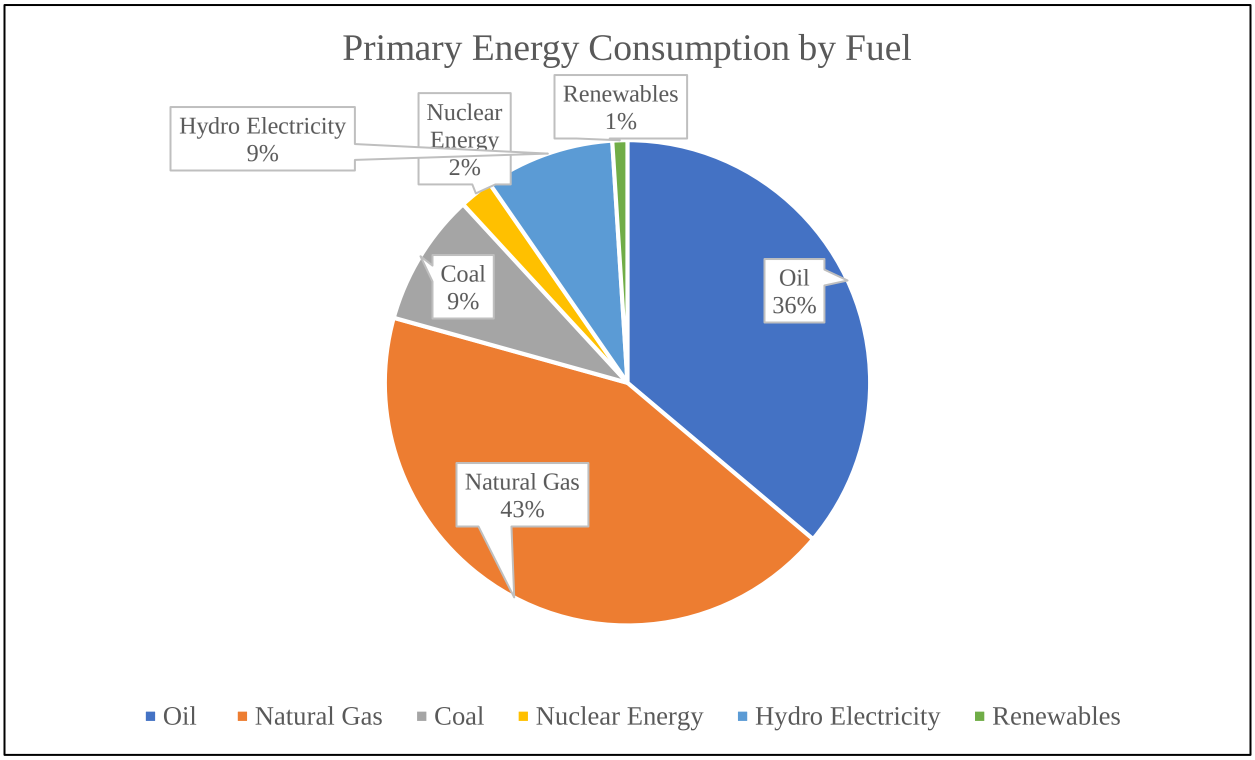

Figure 2 Pakistan Primary Energy Consumption by Fuel

With significant increase in consumption of these fuels, the concentration of CO_2 in the atmosphere has been rising, hence interest of geological sequestration of these CO_2 emissions has been increased.

2.2. Underground Geological Sequestration

For over a decade scientist have been looking into different options and different ways to mitigate carbon emissions spread out in the atmosphere and apart from recommended approach of using less carbon-intensive fuels in major operations [5], underground geological sequestration has also been highly recommended approach where anthropogenic sources of CO_2 emissions stored in deep underground geological formations and avoiding its global greenhouse effect [6].

CO_2 is non-combustible gas, but it is very hazardous in triggering climate change in the region. The major source for CO_2 emissions is power plants [7], that run on fossil fuels and there are many potential geological sites which offer underground sequestration of these anthropogenic sources, which includes saline formations, depleted oil and gas reservoirs. CO_2 is injected in underground geological formations in a supercritical state where most of the gas properties and its conditions are near the phase boundary, as supercritical CO_2 gas it has a higher density than the gaseous state [8].

2.2.1. Geo Sequestration of Carbon

As discussed, there are number of options available for sequestration of CO_2 emissions in underground storage, and no one can deny the potential of CO_2 sequestration from fossil fuel power plants (particularly coal-fired power plants), where highly intensive CO_2 emissions are emitted. Other points sources may also include steel, chemical, and other processing plants operating in the country [9].

After capturing and sequestration of CO_2 from potential sources proper processing and liquefication takes places, and then CO_2 transported to injected sites where gas is injected into the formation for underground geological storage. Geological storage of CO_2 emissions is purely based on the principles and techniques of oil and gas recovery operations and experienced also gained from injected CO_2 in coal bed methane recovery processes. These techniques are not a new phenomenon for underground geological storage and have been adopted worldwide by many countries [10]. The factors like sweep efficiency, injection rates, injection fluid miscibility with reservoir fluid are important factors to be considered in geological sequestration of CO_2 [6].

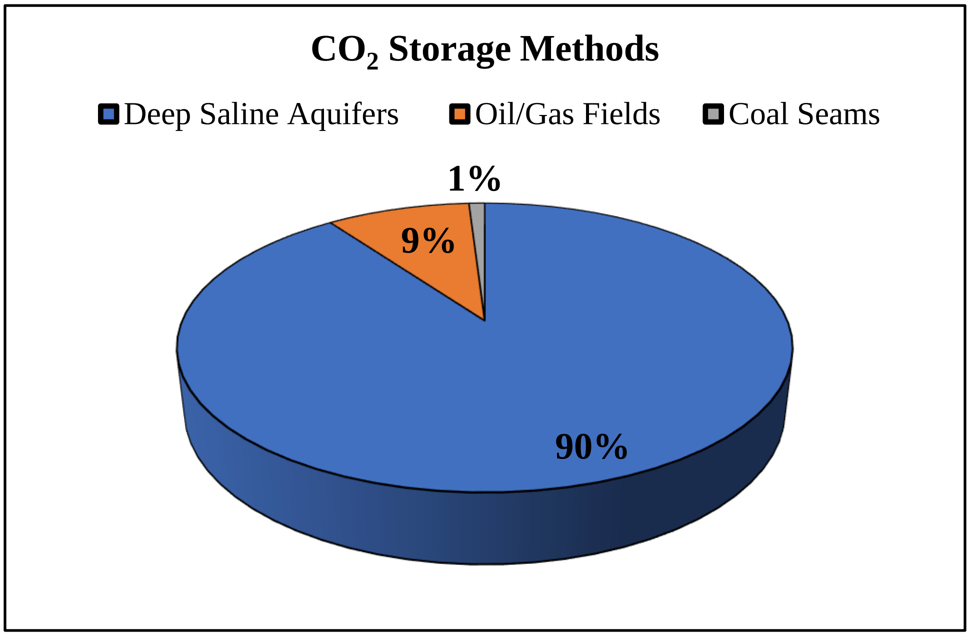

Figure 3 CO_2 Storage Methods

2.2.2. Geological Sites and CO_2 Storage Methods

There still may be some technological advancement needed in carbon sequestration techniques but professionals from the oil and gas industry offer the most expertise in storing CO_2 underground in a porous medium. Mainly two approaches are used for geological storage of CO_2 emissions underground, i) via EOR ii) via High volume CO_2 injection in depleted oil fields or deep saline aquifer [11].

EOR

It is the oil recovery process in which oil recovery can be enhanced by injecting of materials which are not present in the reservoir. This technique has been commercially practiced for many decades. Traditionally, There are many EOR methods including chemical, miscible, and thermal methods but oil recovery via miscible CO_2 injection is more preferred technology over other EOR methods [12]. Figure 4 demonstrates production of oil and gas resources from reservoir to surface, subjected to duration of recovery process.

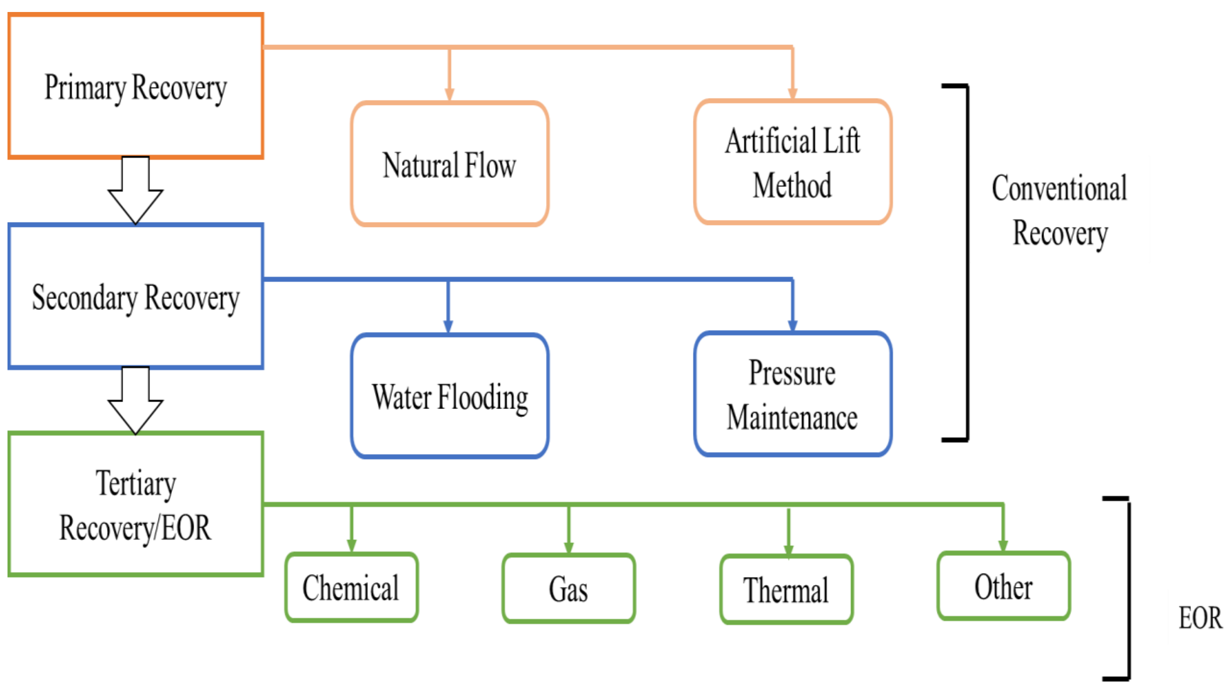

Figure 4 Oil recovery Processes

And it is clearly mentioned in Figure-4, that before implementation of EOR, oil-producing field goes through a number of recovery processes, of which the first stage displaces oil through a natural mechanism called primary recovery, applied during the initial production phase of an oilfield, during the primary phase, reservoir pressure is usually higher than the atmospheric pressure. The primary recovery factor (i.e. the ratio between the oil produced and the total oil in place) ranges between 5-15 % of OOIP [13]. The secondary recovery comes into play to improve oil production rate in the form of injecting fluids, relying on external energy of reservoir fluid. Secondary recovery typically involves water injection in the number of specified injection wells. On average oil recovery from secondary recovery typically ranges from 30-40 % of total Oil in place [14]. After primary and secondary recovery further recovery of crude oil from existing reservoir also possible with another recovery technique known as tertiary recovery also known as EOR.

High Volume CO_2 Injection

It is the most common approach where the bulk amount of CO_2 gas injected in large saline aquifers or in oil reservoirs which are depleted due to the decline in their reservoir pressure. For oil reservoirs this storage method is applicable when oil field has been depleted following primary recovery of oil, and average reservoir pressure is considerably lower than its original reservoir pressure, which is usually at or below the bubble point pressure [11]. when drive mechanisms of typically such reservoirs are supported by water drive, possibly its pore spaces filled out with high saturation of water, if reservoir is not supported by water drive then typically such reservoirs are best choices for gas storage with preferably storage option of natural gas or CO_2.

2.3. EOR via CO_2 Injection (CO_2-EOR)

Almost all processes of EOR, especially miscible injection methods using (CO_2-EOR) injection has been tested at commercial scales worldwide. Successful CO_2-EOR involves following factors,

(i) capillary forces at a microscopic level so that trapped oil is released, (ii) To increase the mobility (inverses of flow resistance) of reservoir oil or decrease the mobility of injection fluids that is required for stable operation [14].

The practice of injecting the bulk amount of CO_2 gas to increase recovery of oil is not a new phenomenon and has been practiced in the past decades. CO_2 has some distinct properties which are more advantageous for any reservoir recovery. CO_2 has two valuable characteristics that make it a good option for using it as an injecting fluid, for this purpose: it is miscible with crude oil, and also it is cheaper or less expensive than other miscible fluids [15]. CO_2 also has a higher solubility in crude oil while injecting at pressures of 700 psi, and dramatically reduced oil viscosity which makes the oil easier to flow at the surface. It also has low critical temperature and pressure and has properties similar to liquid as a dense phase while injection [16].

There are mainly two objectives to use CO_2 for possible recovery in EOR operations: as a fluid which is immiscible and does not mix with oil completely or as a miscible fluid which can be soluble with oil, CO_2-EOR operations with miscible flooding are much more efficient because in miscible flooding CO_2 mixes with light hydrocarbons of oil, becomes mutually soluble with residual oil, and trap oil effectively. Miscible flooding gives more productive results when CO_2 is more compressed (high density) and oil volume contains lighter hydrocarbons [15].

2.3.1 CO_2-EOR Operations Overview

CO_2-EOR is not a new approach for recovery of trapped oil, this technique has been applied commercially previously, oil and gas industry professionals have been using this CO_2-EOR technique for last 40 years specifically in geologically favourable locations. CO_2-EOR used extensively in the U.S. in the mid-1980s primarily in areas of West Texas, and also few areas in Canada & Mexico. The cumulative 100 CO_2-EOR operations in the U.S. had commercially produced more than 200,000 barrels of oil per day [17]. Besides CO_2-EOR plays a major role in the recovery of oil which is not possible by conventional means, it also provides four other notable benefits [18].

First, Sale of potentially hazardous CO_2 gas captured from coal-fired and other power plants. Pakistan is one of the countries facing severe climate change due to both rises in temperature and CO_2 emissions in the atmosphere, the size of the market for the sales of CO_2 emissions have been growing from now to 2030. Sale of CO_2 emissions to CO_2-EOR operating companies will also reduce the operating cost needed to carbon capture and storage (CCS) technology.

Second, while using CO_2 for recovery of oil gives the potential benefit of storing CO_2 gas for a long duration of time in the vicinity of the oil reservoir.

Third, when the volume of CO_2 is injected to produce oil, the recovered crude oil can be termed as carbon-free, when it accounts to determine the difference between the injected volume of CO_2 and volume of CO_2 that has been recovered from production of crude oil.

Fourth, reducing dependency on imported fuels and supporting indigenous exploration of resources, and also potential of building CO_2 pipeline structure and CO_2 capture and storage facilities near powerplants where CO_2 emissions are produced.

2.3.2. CO_2-EOR Injection Technologies

There are different methods of CO_2-EOR where CO_2 can be injected in the reservoir for additional recovery [19].

Continuous CO_2 Injection

It involves continuous CO_2 injection in the oil reservoir until production of slug reached the surface, the ultimate oil recovery is somehow proportional of total CO_2 injection in the injection well. The major drawback going with this technique is that CO_2 having lower viscosity compare to oil migrates and settles at the top, that could result in adverse mobility ratio.

Water Alternative Gas Injection (WAG)

WAG is a combination of two injection methods, i.e. Waterflooding and Gas Flooding, it is the most common CO_2-EOR methods used worldwide, by using this method sweep efficiency of oil can be much improved, and it also overcomes the channeling of CO_2 gas at the top during oil recovery.

Gravity Aided CO_2 Flooding

This technique is proposed when there is the change in the geography of the reservoir and reservoir is tilted from upside front, in such case injection of CO_2 takes place at higher end of the reservoir, while CO_2 produces from its bottom end. There are also other methods available like Huff & Puff, Simultaneous Water Alternative Gas (SWAG) and Hybrid WAG, these methods are used when above methods prove to be non-effective and target reservoir has extensive fractures [19].

Two worldwide issues also has been addressed by CO_2 flooding in general (i) usage of CO_2 as prominent EOR injection fluid for both miscible and immiscible flooding (ii) Underground sequestration and storage of CO_2 gas which removes greenhouse gas emissions from atmosphere, so it takes no wonder how CO_2 storage became highly attractive technique for oil recovery among all EOR techniques.

2.3.3. CO_2 Injection in Fractured Reservoir

This study concentrates on CO_2 injection in carbonate reservoirs including simulations of CO_2 dispersion in the porous and permeable rocks. Carbonate reservoirs are characterized by having very low permeability and very high heterogeneity causing a significant amount of CO_2 to be recycled. The oil production from carbonate reservoir is nearly half the production from sandstone. While the CO_2 used is around 60% or less [20].

CO_2 has the highest recovery factor as compared to other injection gases, there are certainly some issues in availability and handling of CO_2 injection and equipment's, therefore it is very wide to find out minimum possible injection with maximum benefits. Maximum recovery and Net Present Value (NPV) can be achieved with minimum injection [21].

2.3.4. Mechanism of CO_2-EOR

It is the recognized fact that CO_2 injection used for additional recovery of oil mainly because of two characteristics of CO_2, firstly, miscibility of CO_2 gas with oil and second, its cheapness having higher sweep efficiency than other available solvents. The Figure 5 demonstrates typical CO_2-EOR operation activity [22]. The operation involves capturing of CO_2 and storing of CO_2 and injected at higher injection rates 1200 psi or more through the pipeline, meter installed at pipelines measures the exact volume of CO_2 purchased by EOR operating companies. This CO_2 is directed to the injection well, gas may require a compressor to maintain the pressure of injected gas if the distance from injection gas purchased site and operating site is greater. At the production site there may be more than one production well per one injector well, the pattern and combination of injector and producer well determined through computer simulations by taking considerations of oil saturation layer in reservoir, CO_2 gas injected through injection well miscible with hydrocarbons decreases the viscosity and increases the mobility of oil which in result produced the oil and gas at the producer well.

Transistors installed at well head used to calculate the oil and gas volume produced at the surface, these fluids produced at surface are separated. CO_2 is then separated from natural gas and then

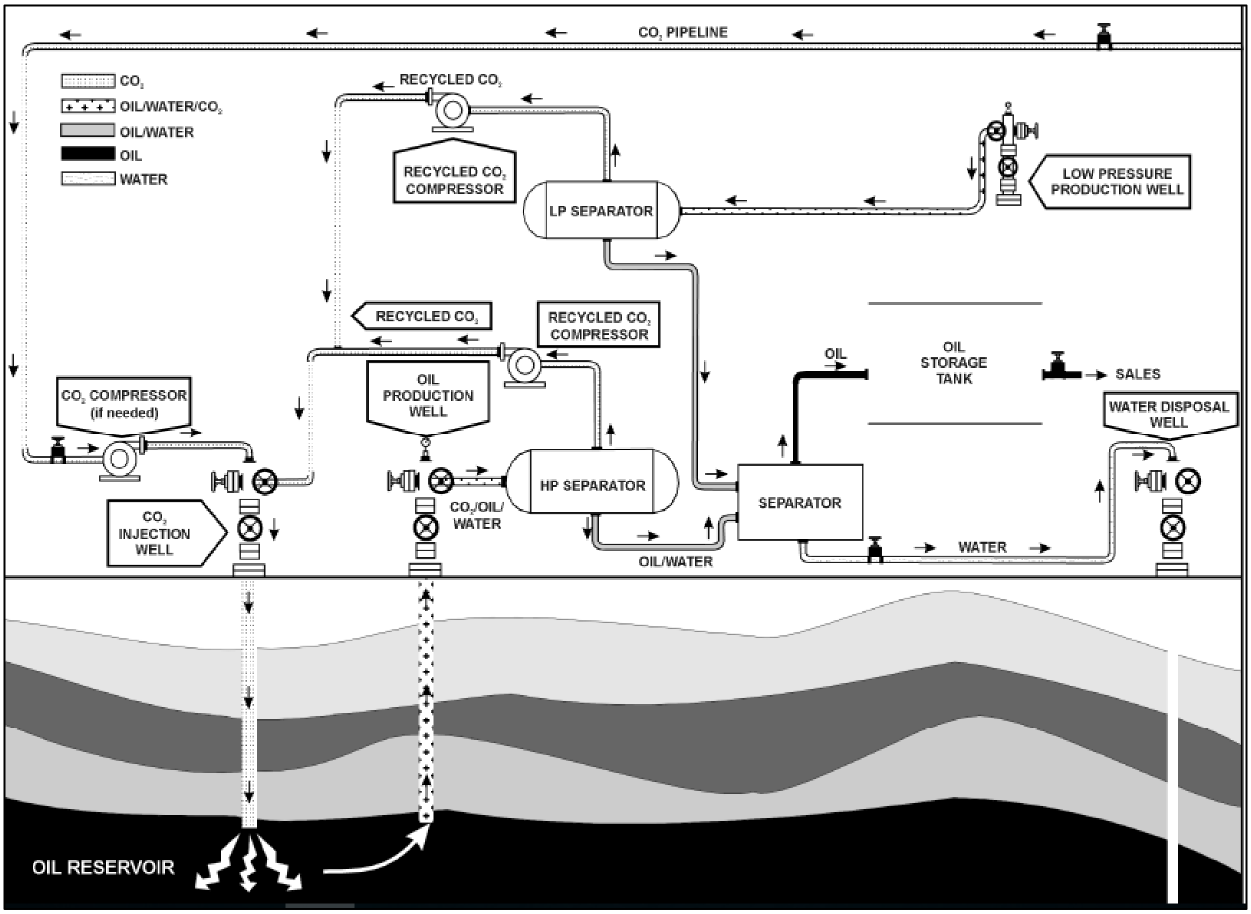

Figure 5 CO_2-EOR Operation (Source EOR Scoping Study)

further compressed and reinjected with new volume of purchased gas at CO_2 storage site. Produced gas goes for the gas processing facility and oil directed to oil storage and stabilization facility [15].

2.3.5. The Energy Needed for CO_2-EOR Operation

Capturing, compression and storing of CO_2 geologically underground is a highly energy-intensive process. CO_2 found in natural form cannot be used directly for CO_2-EOR operation, it has to be converted in supercritical state and then transported through the pipeline to the oil field. In process of CO_2 capture and sequestration some amount of CO_2 emitted into the atmosphere, these CO_2 emissions are either direct emissions or indirect emissions, use of onsite electricity generation gives the direct emission while use of offsite electricity generation gives indirect emissions [23].

To estimate the total requirement of energy in each sequestration and CO_2 emission in the atmosphere, it is necessary to quantify each step of the CO_2 capture and sequestration of CO_2-EOR operation. First, it should be clear from what source CO_2 has been captured either it is fossil fuel plant, ammonia fertilizer, or from somewhere else, and it should also be calculated what percentage of pure CO_2 gas stream has been extracted from CO_2 source. If the CO_2 gas stream been extracted from source is mainly pure still, some emissions may occur when gas is captured, transported to oil field for CO_2-EOR operation, and once CO_2 is transported to oil field more CO_2 emission into the atmosphere takes place because all EOR methods requires major pumping systems and are highly energy-intensive process, therefore, EOR operations are operated mostly through natural gas as external power source.

Emission factors as mentioned in [23] depends on what source has been used for energy consumption, for example, extraction of energy from burning of coal will release more CO_2 than burning of natural gas (117.080lbs/10^6 BTU), and if the CO_2 gas stream is pure (i.e. 98% approximately) it may be compressed through the compression process, for which compression process accounts for 393 kJ/kg-CO_2 and if still there is the requirement for drying of gas it accounts for 8kJ/kg-CO_2 of heat and cooling takes 8kJ/kg-CO_2 of electricity.

Consumption of electrical energy for production of per barrel of crude oil in CO_2-EOR operations are relatively more than thermal EOR methods, as CO_2-EOR methods require more pumping of fluids, injection of gas, separation of formation water and again reinjection of gas, hence it utilizes approximately 5 hp of electrical energy per barrel of oil per day as compared to 0.75 hp of electrical energy in thermal EOR methods.

2.4. Reservoir Characteristics

After the first invention of petroleum reservoir in 1859 at Pennsylvania, the petroleum industry has become one of the fastest growing industries in the world. Even after years of its first invention of oil and gas, professionals keep on looking hydrocarbon reservoirs, these reservoirs comprising of some important characteristics [24], one of them is reservoir depth, the depth of the reservoir is attributed to all the characteristics of the reservoirs, such as deep reservoirs have high reservoir pressure and temperature and while shallow reservoirs have lower pressure and temperature. The accumulations of petroleum resources in reservoir rocks are mainly carbonate and sandstone rocks.

2.4.1. Rock and Fluid Properties

These properties of reservoirs are very much significant for reservoir characterization. Precise information of reservoir rock properties can only be obtained once rock core samples are physically tested in the relevant laboratory. These laboratory tests are called core analysis tests and are subjected for following properties [25]. Rock samples which are analysed in the laboratory can be shown in Figure 6 [26]. Porosity is the ratio of the pore volume to the overall bulk volume. Mathematically equation (2.1) expressed as,

$$\varnothing = \frac{porevolume}{bulkvolume} \qquad (2.1)$$

Figure 6 Rock Core Samples (Source Alberta.ca)

Saturation is fraction of oil, gas, or water occupied by particular fluid (water, oil or gas). Equation (2.2) for Fluid Saturation may expressed as,

$$\text{Fluid Saturation}=\frac{\text{total volume of fluid}}{\text{pore volume}} \qquad (2.2)$$

Permeability is the property of the rock to transmit fluids through its medium, the law that defines the permeability is called Darcy Law. Its SI unit is *Darcy*, but mainly permeabilities quantities are measure in millidarcy (md), 1 Darcy = 1000 md.

2.5. Original Oil in Place

Reserve estimation is the most important aspect of any oil and gas recovery operation, all the exploration activities and seismic surveys are carried out after analysing reports of reserve estimates, and calculation of total original oil in place. Any miscalculation in this estimation can result in great loss and failure of the project. Researchers and other professionals of industry are always recommended to use methods of reserve estimation that have the result of higher accuracy.

Total (OOIP) of a field mainly determined by the following methods,

i. Volumetric
ii. Material Balance Calculation

2.5.1. Volumetric Method

This method is used for new discovery when only one well has been drilled and has not produced for an extended period of time and completely isolated from other reservoirs. It is also said for the volumetric reservoirs that they have constant pore volume, as volumetric reservoirs are completely isolated from its neighboring reservoirs, they do not get any support in form of pressure surge from other adjacent reservoirs, volumetric calculations are generally for dry gas, and wet gas reservoirs [27].

The Equation (2.3) used for reserve determination using the volumetric method is as follows.

$$OOIP = 7758 \times A \times h \times \varnothing \times (1 - Sw) / Bo \qquad (2.3)$$

Where

A = Extent of the reservoir (Acres)

h = Pay thickness (feet)

Ø = Porosity (%)

S_w= Water Saturation

B_o= Oil formation volume factor (Rb/STB)

2.5.2. Material Balance Equation (MBE)

MBE method is the most common tool used by professionals in the oil industry, it gives more leverage than volumetric equation in the estimation of reserves and reservoir development, and MBE equation give precisely calculated form of data for oil in place and cumulative fluid production [28]. In order to calculate precise OOIP from MBE following data needed

- Pressure history
- Production history
- Reservoir rock and fluid property (PVT)

This method is mostly used and reliable tool for calculation of OOIP and drive mechanism, major controlling factor in this method is formation compressibility. The OOIP is determined with follow up to calculations of Equations and laboratory determined PVT properties. The Equation (2.4) is for underground withdrawal.

$$F = Np(Eo + mEg + Ef,w) + WeB \qquad (2.4)$$

Where

F = Underground withdrawal of fluid (Rb)

N_p = Cumulative oil production (bbl)

E_o = Expansion of oil with its originally dissolved gas (Rb/STB)

E_g = Expansion of gas cap (Rb/SCF)

m = Ratio of the initial hydrocarbon pore volume of gas cap to that of oil volume (%)

$E_{f,w}$ = Connate water expansion and pore compaction (Rb/STB)

W_e = Water encroachment (Rb)

B_w = Water formation volume factor (Rb/STB)

For expansion of gas cap (E_o) and underground withdrawal of fluid (F), Equation (2.5) and (2.6) mathematically written as,

$$E_o = (B_o - B_{oi}) + (R_{si} - R_s)B_g \left(Rb / STB\right) \qquad (2.5)$$

$$F = N_p[B_o + (R_p - R_s)B_g] + W_p B_w \left(Rb\right) \qquad (2.6)$$

also, following are the Equations (2.7-2.14) which leads to MBE, and expressed as,

R_p = Producing gas oil ratio (SCF/STB)

R_s = Solution or dissolved gas oil ratio (SCF/STB)

R_i = Initial gas oil ratio (SCF/STB)

B_o = Oil formation volume factor (Rb/SCF)

B_o = Initial Oil formation volume factor (Rb/SCF)

$$E_g = B_{oi}(B_g / B_{gi} - 1), \ \left(Rb / STB\right) \qquad (2.7)$$

$$E_{f,w} = \left(1 + m\right) \ Boi[C_w S_{wc} + C_f) \ dp / (1 - S_{wc})], \ \left(Rb / STB\right) \qquad (2.8)$$

$$\text{Oil Compressibility } (C_o) = (B_{ob} - B_{oi}) \ / \ (B_{oi} dP), \ \left(1 / psi\right) \qquad (2.9)$$

$$\text{Total Compressibility } (C_t) = C_o S_o + C_g S_g + C_w S_w + C_f, \ \left(1 / psi\right) \qquad (2.10)$$

$$\text{Effective Compressibility} = C_{oe} = C_t / S_o, \text{ where } S_o = 1 - Sw - Sg, \ \left(1 / psi\right) \qquad (2.11)$$

$$C_{oe} = C_o + S_w C_w \ / \ (1 - S_w) + C_f \ / \ (1 - S_w) \text{ where } S_g = 0 \ \left(\text{when there is no free gas}\right) \qquad (2.12)$$

Since we have assumed that the reservoir is above the bubble point.

m = 0 and $R_p = R_s = R_{si}$ and assume negligible water influx, the equation (2.9.4) reduces to,

$$F = N\,(E_o + E_{f,w}) \qquad (2.13)$$

and finally

$$Oil\ in\ Place\ (N) = F/(E_o + E_{f,w}),\ (STB) \qquad (2.14)$$

2.6. Reservoir Simulation

Black oil and compositional reservoir simulation are widely used by oil and gas industry professional; this type of numerical simulation provides flexibility in which all important geological and stratigraphically aspects can be visualized. The model developed by a different set of cartesian grids, these grids specifies the important property of model geometry where each block is defined and it also specifies the geometry of the grid block [29]. When commencing numerical simulation of black oil or compositional model, numerical model build the single well model for reservoirs, different reservoir simulators uses different assumptions to simulate oil, gas or water flows, the assumptions used can be Fick Diffusion Law, Dual Porosity Model, Equilibrium Initialization, etc. what assumptions are chose to use in simulation has very important effect on the results of reservoir simulation [30]. This research uses the ECLIPSE reservoir simulator, made by Schlumberger Oil field services.

2.6.1. Eclipse Reservoir Simulator

ECLIPSE is a reservoir simulation launcher made by Schlumberger Oil Field Services, it has [31]

- Fully-implicit, three phases, three-dimensional, general purpose black oil simulator with gas condensate option.
- It can be used to simulate 1, 2 or 3 phase systems. Two-phase options (oil/water, oil/gas, gas/water) are solved as two-component systems, in addition to gas dissolving in oil (variable

bubble point pressure or gas/oil ratio), ECLIPSE 100 may also be used to model oil vaporizing in gas (variable dew point pressure or oil/gas ratio).

- Both corner-point and conventional block-center geometry options are available in ECLIPSE. Radial and Cartesian block-center options are available in 1, 2 or 3 dimensions. A 3D radial option completes the circle allowing flow to take place across the 0/360 degrees interface.
- To run the simulation you need an input file with all data concerning the reservoir and process of its exploitation.

2.7. Pakistan Oil Field and EOR

Oil and Gas production in Pakistan mostly comes from the primary phase of the recovery process. Pakistan known total oil reserves are around 27 Billion barrels and approximate recoverable reserves are 936 Million barrels [32] and by looking at the current production rate indigenous resources of Pakistan will face the backlash in coming years. In December 2018, Pakistan total indigenous crude oil production was 90,000 bbl/day, averaged daily inflow of crude oil production in Pakistan is 67,000 bbl/day from 1994 to 2018, with peak production rate of 97,000 bbl/day in December 2016 [33]. There is still large volume of oil remains after primary recovery, and by looking at the current production trend in Pakistan it is assessed around more than one billion barrels of untapped oil reserves are still in place in Pakistan and this residual untapped oil is certainly the target of EOR technologies, the recovered oil from such unconventional techniques can surely contribute in country`s economy by reducing its dependence on imported fuel.

2.8. Summary

Since the industrial revolution, there has been a rise in global emissions of CO_2 along with other GHG, and this increase has led to some serious consequences of environmental threats to specifically to countries which are very vulnerable to climate change. This chapter gives an overview of the literature describing the methods for underground geological sequestration of carbon and storage methods of CO_2. The overview also is given on what best practices are considered when CO_2 injected into depleted oil reservoir for geological storage through different injection technologies described in this chapter. Brief introduction of ECLIPSE Reservoir Simulator also given which seems to be best-suited software to visualize the 3D plot of the reservoir model and analyse other reservoir properties.

2.9. References

[1] G. Mundaca, “How much can CO_2 emissions be reduced if fossil fuel subsidies are removed?,” *Energy Econ.*, vol. 64, pp. 91–104, 2017.

[2] D. Coady, I. Parry, L. Sears, and B. Shang, “How Large Are Global Fossil Fuel Subsidies?,” *World Dev.*, vol. 91, pp. 11–27, 2017.

[3] B. S. R. of W. E. 2018 Energy, “67 th edition Contents is one of the most widely respected,” 2018.

[4] T. Aized, M. Shahid, A. A. Bhatti, M. Saleem, and G. Anandarajah, “Energy security and renewable energy policy analysis of Pakistan,” *Renew. Sustain. Energy Rev.*, vol. 84, no. September 2016, pp. 155–169, 2018.

[5] I. Panel and C. Change, *Carbon Dioxide Capture*. 2013.

[6] R. Shukla, P. Ranjith, A. Haque, and X. Choi, “A review of studies on CO_2 sequestration and caprock integrity,” *Fuel*, vol. 89, no. 10, pp. 2651–2664, 2010.

[7] B. Lin and M. Y. Raza, “Analysis of energy related CO_2 emissions in Pakistan,” *J. Clean. Prod.*, vol. 219, pp. 981–993, 2019.

[8] S. Bachu, “<Bachu 2000.pdf>,” vol. 41, pp. 953–970, 2000.

[9] European Commission, “The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) - Strategic Research Agenda,” pp. 1–49, 2006.

[10] C. M. White *et al.*, “Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery - A review,” *Energy and Fuels*, vol. 19, no. 3, pp. 659–724, 2005.

[11] C. Ehlig-Economides and M. J. Economides, “Sequestering carbon dioxide in a closed underground volume,” *J. Pet. Sci. Eng.*, vol. 70, no. 1–2, pp. 123–130, 2010.

[12] L. W. Lake, R. L. Schmidt, and P. B. Venuto, “A Niche for Enhanced Oil Recovery in the 1990s Aging fields and dwindling prospects for finding new , large reserves are turning attention to improving,” *Most*, vol. 17, no. 17, pp. 62–67, 1992.

[13] D. G. Jrc, *in the European Energy System*, no. December. 2005.

[14] G. P. W. Don W Green, *Book_Enhanced Oil Recovery Willhite.pdf*. 1998.

[15] C. C. and A. C. F. C. D. Melzer, L. Stephen, "Carbon Dioxide Enhanced Oil Recovery," no. February, p. 18, 2012.

[16] W. L. Holm, "Evolution of the Carbon Dioxide Flooding Processes," *J. Pet. Technol.*, vol. 39, no. 11, pp. 1337–1342, 1987.

[17] M. Godec, V. Kuuskraa, T. Van Leeuwen, L. Stephen Melzer, and N. Wildgust, "CO_2 storage in depleted oil fields: The worldwide potential for carbon dioxide enhanced oil recovery," *Energy Procedia*, vol. 4, pp. 2162–2169, 2011.

[18] R. C. Ferguson, C. Nichols, T. Van Leeuwen, and V. A. Kuuskraa, "Storing CO_2 with enhanced oil recovery," *Energy Procedia*, vol. 1, no. 1, pp. 1989–1996, 2009.

[19] F. M. Nasir and Y. Y. Chong, "10.1.1.687.7228," *Int. J. Eng. Technol.*, vol. 09, no. 10, 2009.

[20] N. I. Furuvik and B. M. Halvorsen, "Simulation of CO_2 injection in fractured oil reservoir," pp. 347–355, 2015.

[21] S. Ahmed, A. M. Khakwani, I. Ahmed, and O. H. Khan, "Enhancing Recoveries from a Low Permeable Gas-Condensate Reservoir through Hydraulic-Fracturing and EOR Technologies," *PAPG/SPE Pakistan Sect. Annu. Tech. Conf. Exhib.*, 2016.

[22] E. Oil and R. Scoping, "Enhanced Oil Recovery Scoping Study," 1999.

[23] a T. F. S. Gaspar, S. B. Suslick, D. F. Ferreira, G. a C. Lima, and S. U. Campinas, "SPE 94922 Economic Evaluation of Oil Production Project with EOR : CO_2 Sequestration in Depleted Oil Field," 2005.

[24] Y. Abhijit, *Petroleum Reservoir Rock and Fluid Properties Petroleum Reservoir Rock and Fluid Properties*. .

[25] T. Ahmed, *Reservoir Engineering Handbook (2nd Edition)*. 2001.

[26] “UofA EOGRRC Services.” [Online]. Available: https://sites.ualberta.ca/~tayfun/eogrrc/Behnam-research.html. [Accessed: 20-Jun-2019].

[27] Nnaemeka Ezekwe, *P E T Ro L E U M R E S E Rvo I R*. 2010.

[28] A. H. Ramadan and S. A. Shedid, “Improved material balance equation (MBE) for gas-condensate reservoirs considering significant water vaporization,” *Egypt. J. Pet.*, vol. 27, no. 4, pp. 1209–1214, 2018.

[29] Y. Xu, B. R. B. Fernandes, F. Marcondes, and K. Sepehrnoori, “Embedded discrete fracture modeling for compositional reservoir simulation using corner-point grids,” *J. Pet. Sci. Eng.*, vol. 177, no. June 2018, pp. 41–52, 2019.

[30] J. Kang, X. Fu, S. Liang, X. Li, X. Chen, and Z. Wang, “A numerical simulation study on the characteristics of the gas production profile and its formation mechanisms for different dip angles in coal reservoirs,” *J. Pet. Sci. Eng.*, p. 106198, 2019.

[31] “ECLIPSE Industry Reference Reservoir Simulator.” [Online]. Available: https://www.software.slb.com/products/eclipse. [Accessed: 19-Jun-2019].

[32] M. A. Buriro and M. M. Hamza, “SPE 163124 Enhanced Oil Recovery : A Future For Pakistan,” 2012.

[33] “Pakistan Crude Oil Production | 2019 | Data | Chart | Calendar | Forecast.” [Online]. Available: https://tradingeconomics.com/pakistan/crude-oil-production. [Accessed: 29-Apr-2019].

Chapter 3

Methodology & Site Selection

3.1. The Site Selection

There are many oil fields in Pakistan which had continuously given oil production during its primary phase but now are depleted, and warrant for recovery of oil through secondary and tertiary recovery processes. Work has already been carried out on many of the Pakistani fields, and one such field is the case study of this research project and it is unanimously named as field XYZ.

This field XYZ located in the eastern Potwar Basin of Pakistan, this field has fractured carbonate reservoir and comprising of two producing formations; Chorgali and Sakesar. This field was explored in 1980 by Gulf Oil exploration company [1]. During exploration of first well, hydrocarbons were observed in both Chorgali and Sakesar formation. Well was tested and initial oil production of 20 bbl/day was recorded. As such low production was not economical for the company, hence the company declared this well as non-commercial and after this field was taken over by Pakistani E&P company.

The Pakistani local company successfully tested commercial hydrocarbons reserves in Sakesar formation and the field come on regular production in 1989 with oil rate of 4000 barrels/day with the initial reservoir pressure recorded as 5700 psi. and the bubble point pressure (P_b) measured as 2950 psi, this bubble point relieves the important information regarding the saturation of gas in the oil reservoir and determines free saturation of gas in the oil [2].

3.1.1. Criteria for Site Selection

Anthropogenic sources of CO_2 emissions, which tends to be increasing each year is the real threat for people living on this planet with perspective to climate change [3], these unwanted CO_2 emissions can be mitigated through number of processes and underground geological sequestration is one of through EOR method is one of it [4]. Well, there are many particular criteria’s which have to be considered when selecting a potential field for geological sequestration of CO_2. The Figure 7 is the systematic flow chart of this criteria followed for CO_2 sequestration and EOR [5].

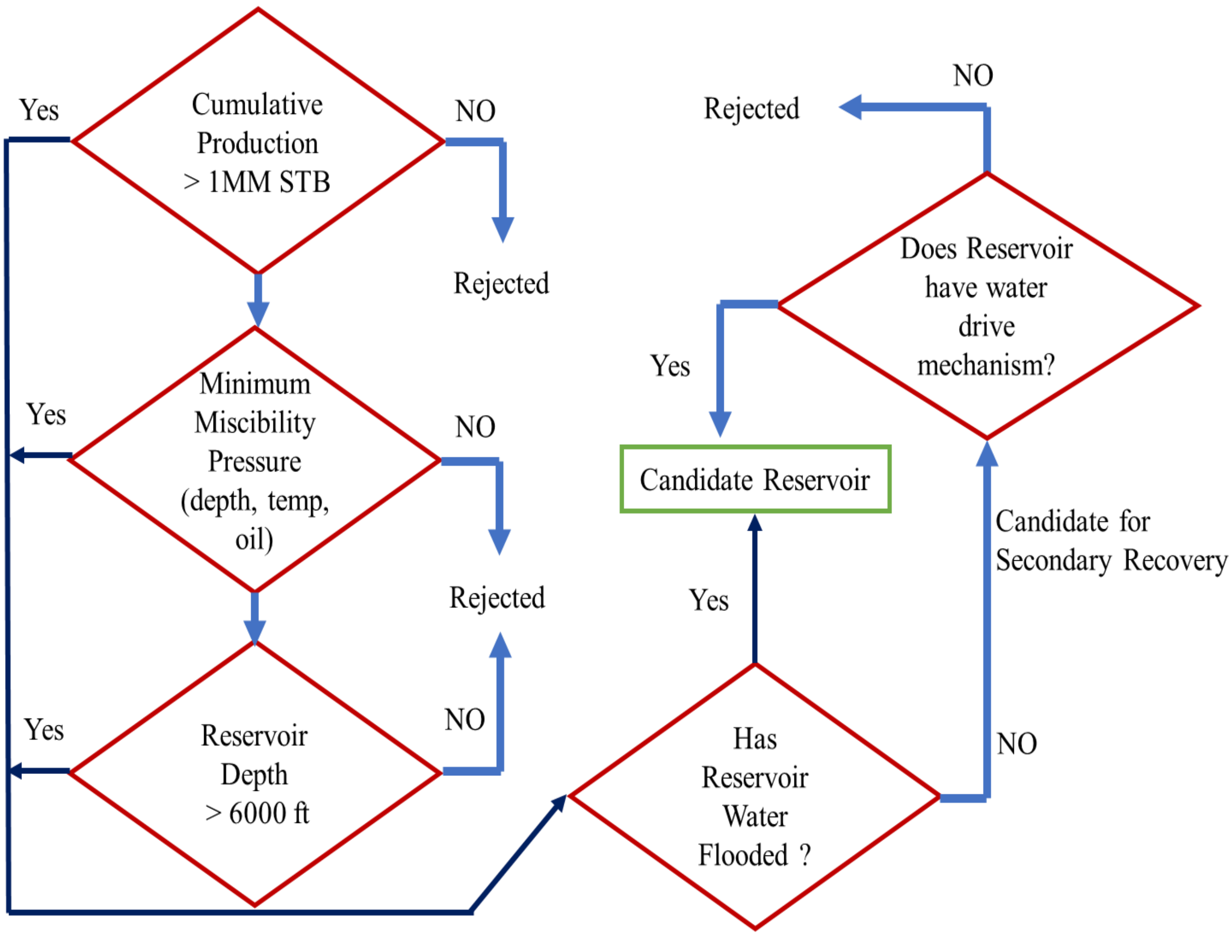

Figure 7 Site Selection Criteria for CO_2 Injection

The site selection criteria is mainly depending on the factors of cumulative oil reserves, cumulative oil production, minimum miscible pressure, and field having the previous history of water flooding.

3.2. Technical Parameters

Technical components of the reservoir system are selected from the previous research studies taken on the same reservoir model and are selected on the basis of their high value standard. The selected site has been the only site in Pakistan, where the operational company has implemented secondary recovery via water flooding, the parameters for this secondary recovery has also been incorporated into the new reservoir model.

3.2.1. Field Pressure History

Table 1 presents the reservoir pressure history of Sakesar formation, as the field was discovered early in the year 1989, the operating companies acquired bottom hole pressure in the same producing year. Pressure is also calculated at fixed datum such that precise hydrostatic potential could be calculated [6].

Table 1 Sakesar Pressure History

Date	Reservoir Pressure	Avg: Pressure at Datum (psia)
22.08.89	5523.7	5670.5
29.11.89	5575	5589
09.03.90	5336	-
29.03.90	5292	5283.5
22.10.90	4798	4788.6
23.03.91	4500	4487
06.06.92	3465	3455
16.12.92	3035	3026
24.11.93	2698	2709
28.08.95	2384	2477
14.08.96	3200	3313

Table 2 presents the field pressure history for other producing.

Table 2 Chorgali Pressure History

Date	Reservoir Pressure	Avg: Pressure at Datum (psia)
23.9.90	5271+	5393
15.10.90	4905	5070.2
26.03.91	2730	851.6

3.2.2. PVT Analysis

Pressure, Volume, Temperature (PVT) analysis are the properties which are routinely used during characterization of any reservoir properties to the software, and also for other simulation work [7]. Table 3 represents the values given for PVT analysis.

Table 3 PVT Analysis

Pressure (psi)	GOR SCF/STB	Bo RB/STB
5000	989	1.568
4500	989	1.579
4000	989	1.592
3500	989	1.608
2934	989	1.626
2600	896	1.546
2200	782	1.469
1800	667	1.409
1400	554	1.3349
1000	477	1.292
600	329	1.23
283	167	1.162

Figure 8 demonstrates the pressure curve for sakesar formation, and as seen pressure declined to as low as below bubble point pressure.

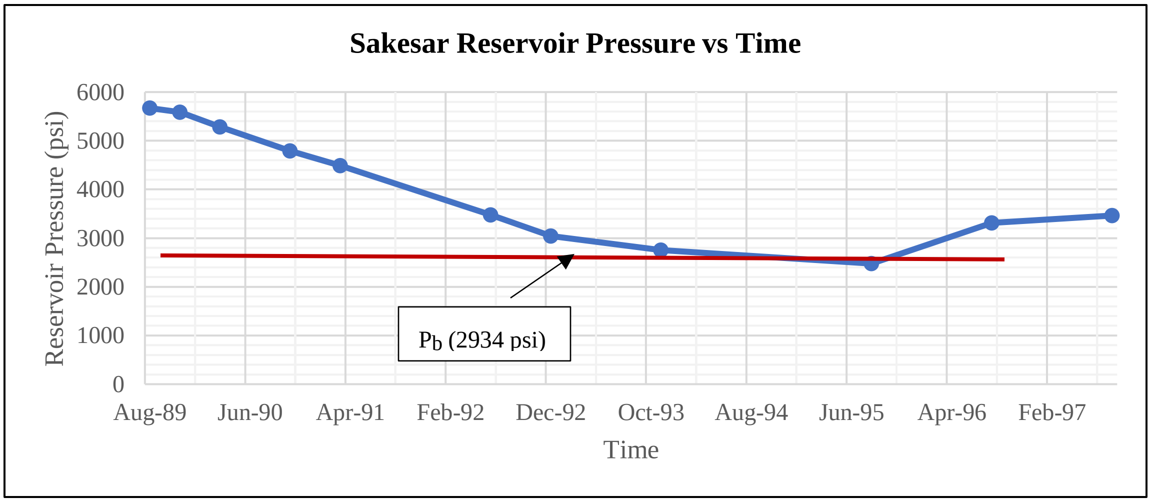

Figure 8 Sakesar Pressure History

Figure 9 depicts the same situation of Chorgali formation as pressure in this formation also had gone past below bubble point pressure which subsequently declined oil production, the pressure of the reservoir declined from 5708 psi to 2477 psi. As a result of such low production water flooding recommended for this field and water injection was started in Sakesar formation.

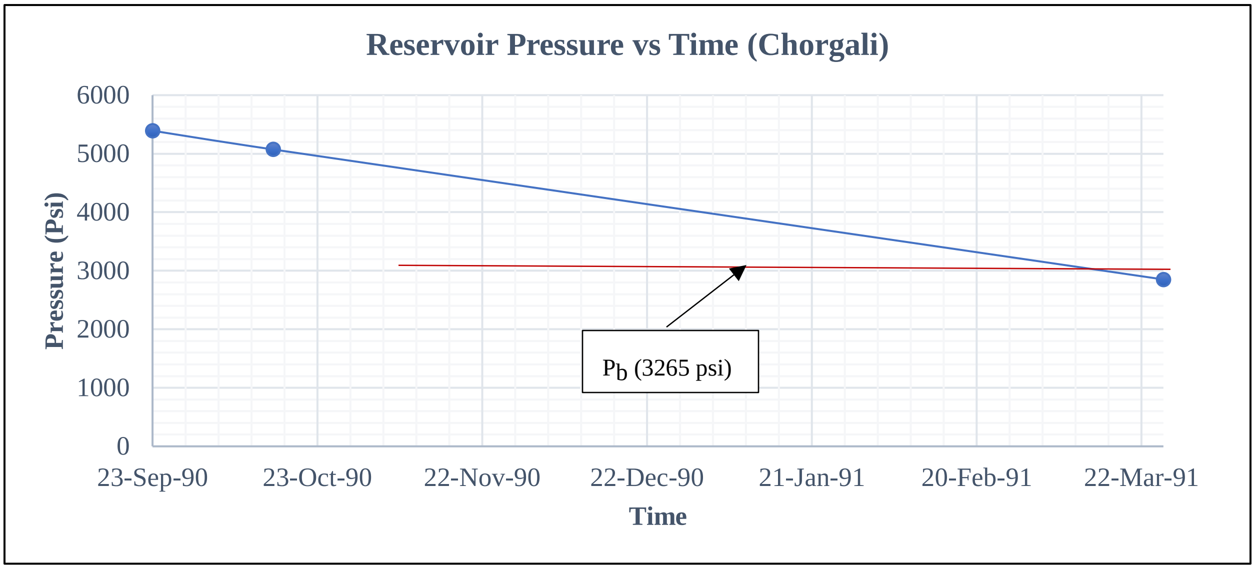

Figure 9 Chorgali Pressure History

3.2.3. Field Reserves

The structure of XYZ field is located in the eastern part of the Potwar Basin. The fractured carbonate reservoir comprises of two producing formations; Chorgali and Sakesar. The said structure was first explored in 1980. Hydrocarbons were observed in both Chorgali as well as in the Sakesar formation.

To-date, 4 wells have been drilled on this structure. Two of these wells are producers while the third well is water injector. Another well was abandoned due to mechanical problems. The cumulative production as of October 2016, is about 13.83 MMSTB oil from the field.

3.2.4. Reservoir Fluid Properties

Fluid Properties data for both Chorgali and Sakesar Formation are given in below Table, these same properties used for initialization of simulating the model in reservoir pressure history and characterization of PVT properties.

Table 4 represents reservoir fluid properties values for both sakesar and chorgali formation.

Table 4 Reservoir Fluid Properties

Property	**Sakesar**	**Chorgali**
Oil Gravity (°API)	33.5	33.1
Original Bubble Point Pressure (Pb), psi	2934	3265
Gas Solubility (Rs) at Pb (SCF/STB)	989	1083.5
Oil Formation Volume Factor (Bo) at Pb (RB/STB)	1.622	1.644
Oil Viscosity (µo), cp	0.252	0.279
Gas Gravity	0.839	0.846
Gas formation volume Factor (Bg) at Pb (Rb/MSCF)	0.9735	0.9616
Gas Viscosity µg at Pb (cp)	0.0210	0.0214

The properties given in the Table 5 are the core reservoir properties, given as

Table 5 Reservoir Properties

Oil Saturation (S_o)	20%
Water Saturation (W_o)	80%
Porosity (Ø)	1.5-3.5 %
Formation Salinity (produced water)	2,800 PPM
Reservoir Temperature at Datum Depth of 8,100 ft	268°F
Pressure Gradient	0.29 psi/ft
Reservoir Pressure (Chorgali)	5,392 psi
Reservoir Pressure (Sakesar)	5,709 psi
Compressibility (cf)	not known precisely

Given 20% oil saturation falls below primary recovery and may not be recoverable in the existing operating system, hence it was necessary to implement techniques for additional oil recovery. It is also noted that formation salinity of produced water is 2,800 PPM, while salinity of injected water is 500 PPM. The more chloride content in produced water is probably due to contamination of residual formation.

3.3. Economic Parameters

Economic parameters are the major part of any EOR project, capital cost estimates, CO_2 storage and sequestration cost, are important investment parameters for the design of the CO_2-EOR project while the economic framework is also mentioned during system design.

3.4. History of Water Injection at Selected Site

Water Injection at field XYZ Well was started in early 1996. The recommended water injection rate was 12,000 bbl/day. Oil and gas production started to increase. The operating company attained the maximum oil production, 3,890 bbl/day, maximum gas production 3.2 MMSCFD in January in the following year of water injection operation.

Total injected water at the injection well is 21 MMBBLS with the total fluid withdrawal from producing well is 20.6 MMBBLS. Vacated pore spaces of the reservoir rocks have been filled almost with water having sufficient energy to produce un-depleted portion of the reservoir. Currently, the water cut is increased from 82% to 85%.

It is recommended in simulation studies that present rate of water injection, should be maintained because its reduction will, in turn, reduce oil production rate without affecting water/oil ratio, thus would prolong depletion period of the reservoir and may also adversely affect the ultimate recovery [8].

3.5. Field Production History

Figure 9 and Figure 10 describes overall production history of both producing formation of this depleted field, it shows both formations had initially produced good natural recoveries started from 1989 with production of 800 bbl/M and 1200 bbl/M for both and Sakesar and Chorgali formation respectively, however sharp decline in reservoir pressure halted the production rate and now few barrels of constant oil production has been maintained with the help of water injection.

.

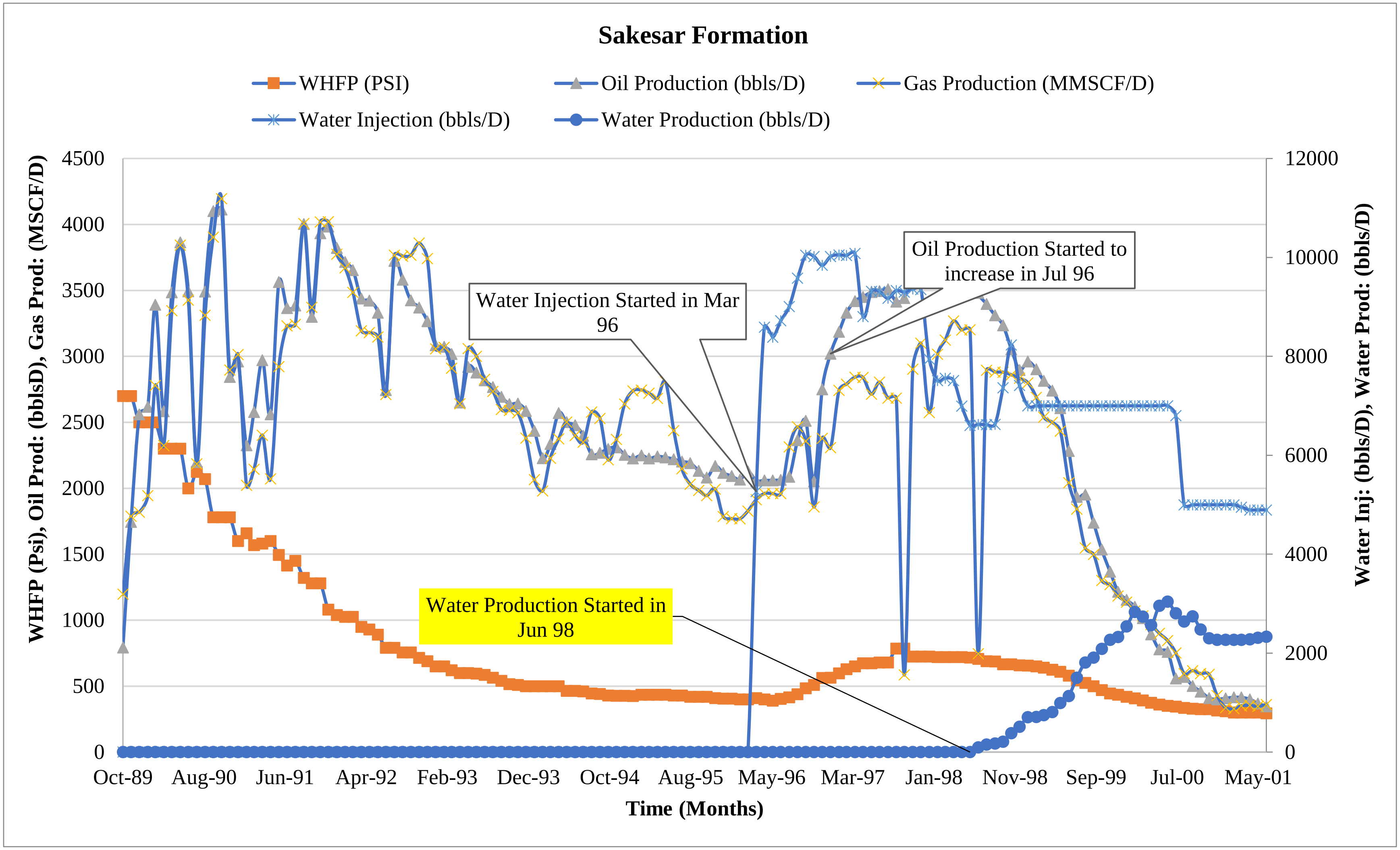

Figure 10 Sakesar Production Profile

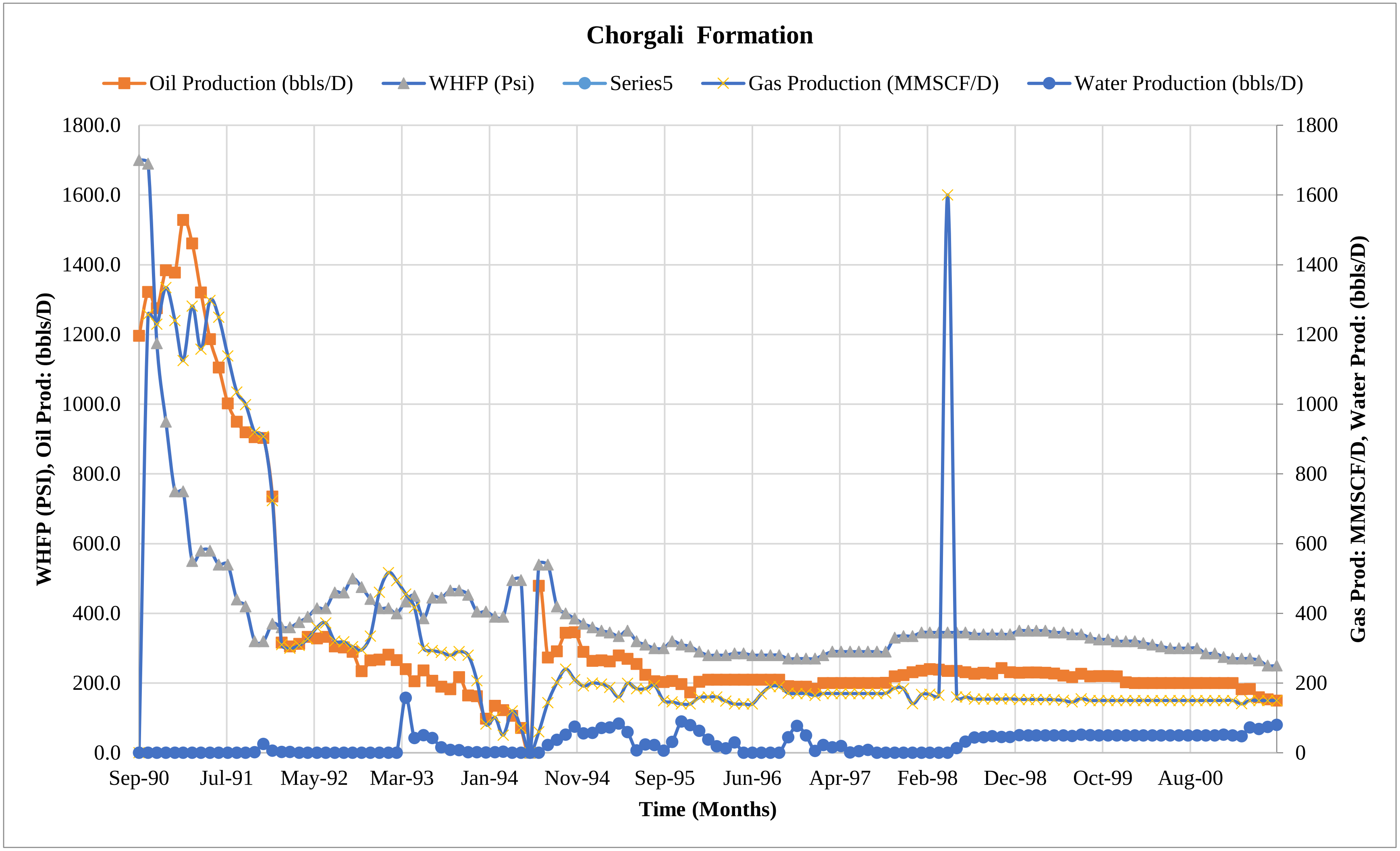

Figure 11 Chorgali Pressure Profile

3.6. Organization of the Simulation Work

The organization of the simulation work follows by first establishing base case simulation work by incorporating all the data acquired through site selection, and also evaluating all the parameters involved in the base case. Figure 12 illustrates the step by step process for reservoir modelling, following base case simulation, one additional model developed for underground geological sequestration of CO_2 emissions in which all the result is analysed where CO_2 injection has the major effect. All the simulation work is done by ECLIPSE reservoir simulator software.

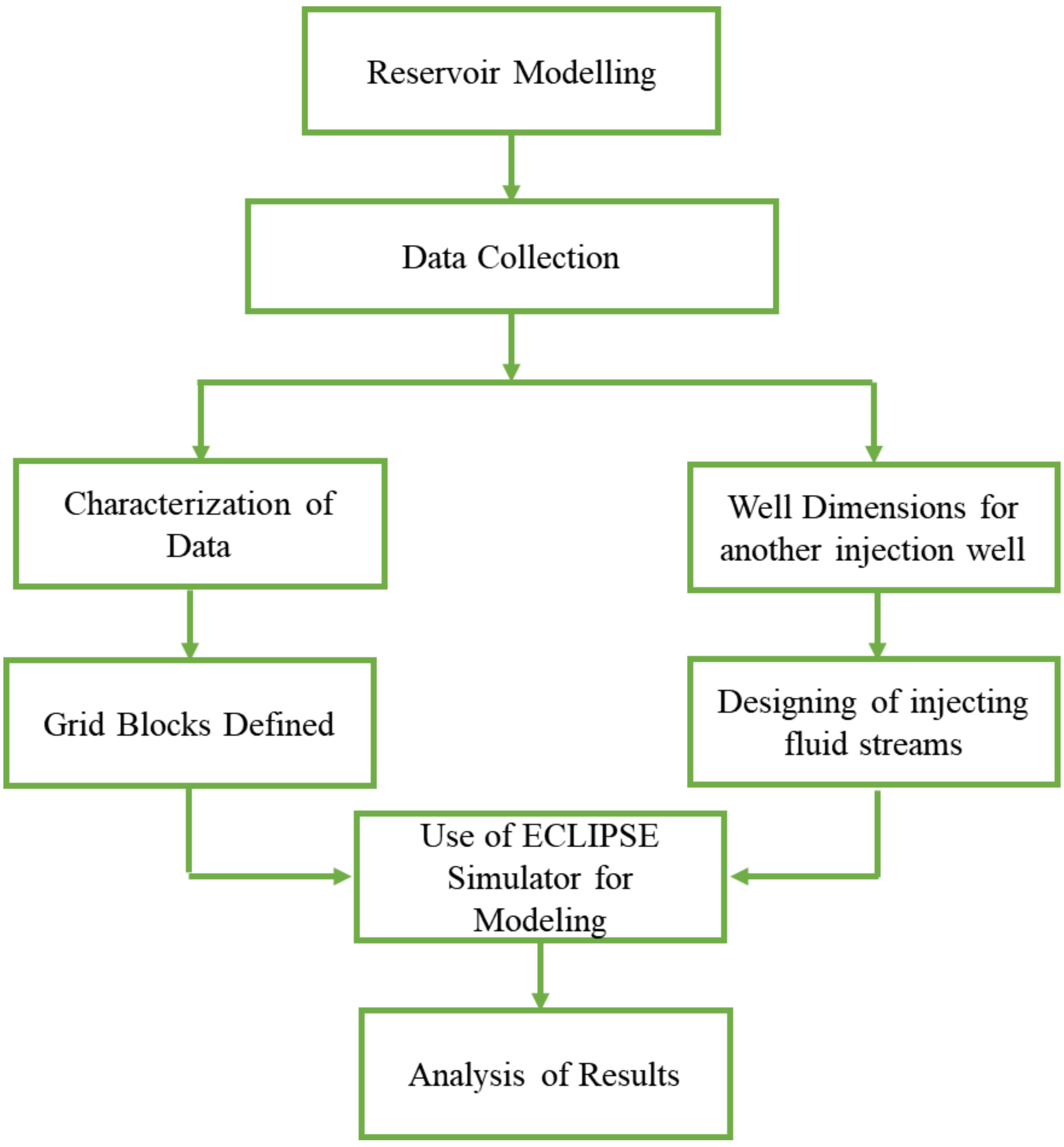

Figure 12 Reservoir Modelling Methodology

3.7. Methodology for CO_2 Injection

There has been the probability-based methodology for different geological sequestration projects for different sites, the conduct of a geological survey is necessary for precise assessment [9], however there is no need to follow point to point methodology when selected site is oil and gas field because major assessments and important surveys had already been done during running of high upstream energy projects [10]. Figure 13 illustrates the methodology followed in implementing injection technique in oil reservoir of depleted field, where CO_2 fluid and its rate of injection will be the input variables of this research while other parameters will be the output variables.

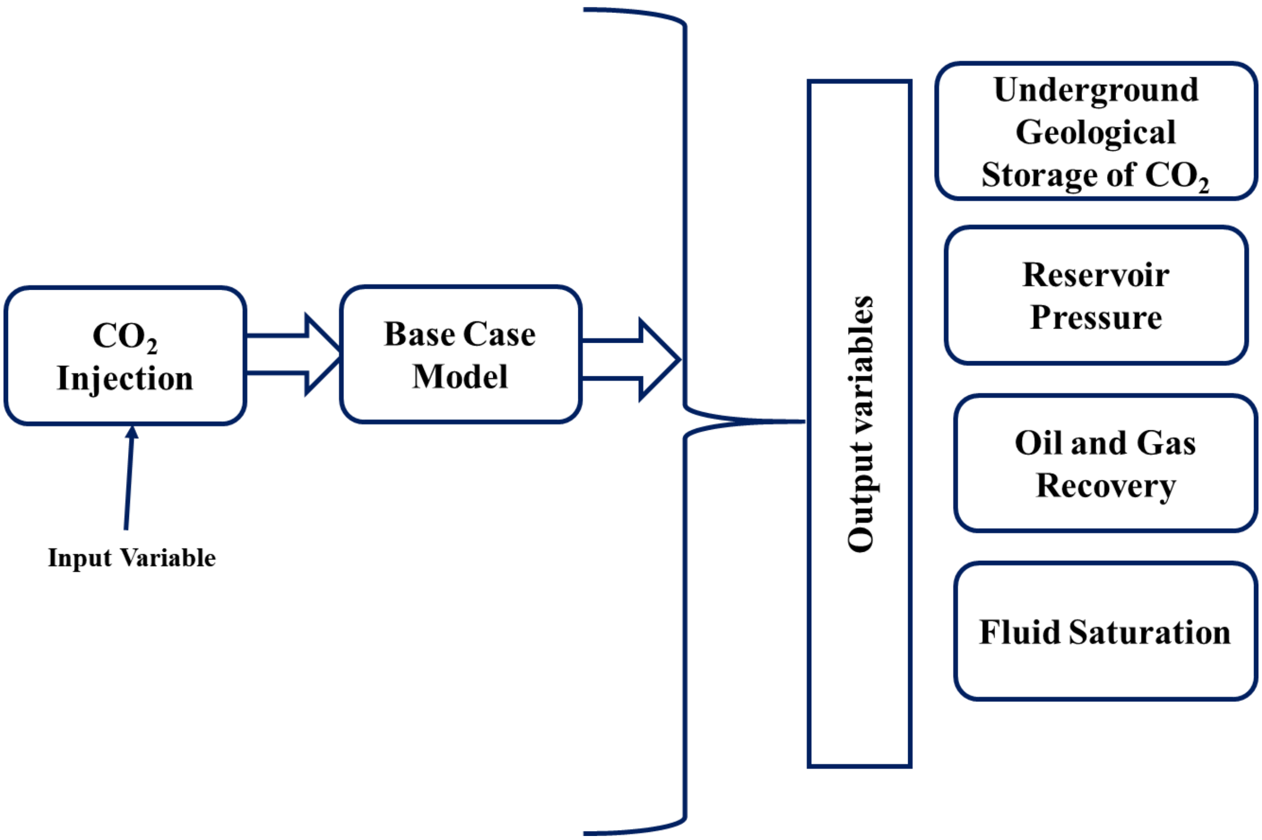

Figure 13 Methodology for CO_2 Injection

3.8. Summary

This chapter describes the methodology to carry out this research work. For the reservoir modelling ECLIPSE reservoir simulator is used and with the help of this simulating tool, the base case reservoir model is compared with three cases having different injection rates of CO_2, and it was analysed how this CO_2 as an injecting fluid has a greater effect on the rate of oil production, gas production and other productive parameters of reservoir of the selected site in Pakistan for EOR. After making of model and forecasting the results are validated and analysed.

3.9. References

[1] M. S. K. Jadoon, A. Hameed, and M. M. Akram, “An Integrated Reservoir Simulation Study of Fimkasser Oil Field,” vol. 13, no. June, pp. 37–58, 2003.

[2] T. Ahmed, *Reservoir Engineering Handbook (2nd Edition)*. 2001.

[3] Y. Liu, P. Wang, M. Yang, Y. Zhao, J. Zhao, and Y. Song, “CO_2 sequestration in depleted methane hydrate sandy reservoirs,” *J. Nat. Gas Sci. Eng.*, vol. 49, no. June 2017, pp. 428–434, 2018.

[4] S. Bachu, “<Bachu 2000.pdf>,” vol. 41, pp. 953–970, 2000.

[5] S. Bachu, “From Regional Characterization to Site Selection,” *Energy Convers. Manag.*, vol. 41, no. 9, pp. 87–102, 2002.

[6] S. A. Alavian, “Sayyed Ahmad Alavian Modeling CO_2 Injection in Fractured Reservoirs Using Single Matrix Block Systems,” no. October, 2011.

[7] H. A. Vásquez Haro, M. S. de P. Gomes, and L. G. Rodrigues, “Numerical analysis of carbon dioxide injection into a high permeability layer for CO_2-EOR projects,” *J. Pet. Sci. Eng.*, vol. 171, no. May, pp. 164–174, 2018.

[8] J. O. Adegbite, E. W. Al-Shalabi, and B. Ghosh, “Geochemical modeling of engineered water injection effect on oil recovery from carbonate cores,” *J. Pet. Sci. Eng.*, vol. 170, no. December 2017, pp. 696–711, 2018.

[9] L. M. Valle, R. Rodríguez, C. Grima, and C. Martínez, “Effects of supercritical CO_2 injection on sandstone wettability and capillary trapping,” *Int. J. Greenh. Gas Control*, vol. 78, no. July, pp. 341–348, 2018.

[10] M. K. Verma, “Fundamentals of Carbon Dioxide-Enhanced Oil Recovery (CO_2-EOR)—A Supporting Document of the Assessment Methodology for Hydrocarbon Recovery Using CO_2-EOR Associated with Carbon Sequestration,” *U.S. Geol. Surv.*, p. 19, 2015.

Chapter 4

Results and Discussion

This chapter comprises of the results and discussions, as discussed, the core area of this research is to mitigate CO_2 emissions and investigate the potential of underground geological storage in the depleted oil field and also to analyse the effect of CO_2 injection on possible EOR of that field. For this purpose, the first reservoir model has been established of the base case of the selected field, and then CO_2 injection technique applied by adding another injection well using CO_2 as injection fluid with three different injection rates. The simulation results are forecasted till 2025. Detailed steps followed for objectives of this study are discussed below.

4.1. Estimation of OOIP

4.1.1. OOIP in Sakesar

This research Simulating study reported the range of OOIP of Sakesar formation from 20.9 MMSTB to 56.6 MMSTB depending upon the value of rock compressibility used. Figure 14 depicts the best estimate for Sakesar formation was 35.4 MMSTB for rock compressibility (C_f) of 2.5 x 10^{-5} /psi.

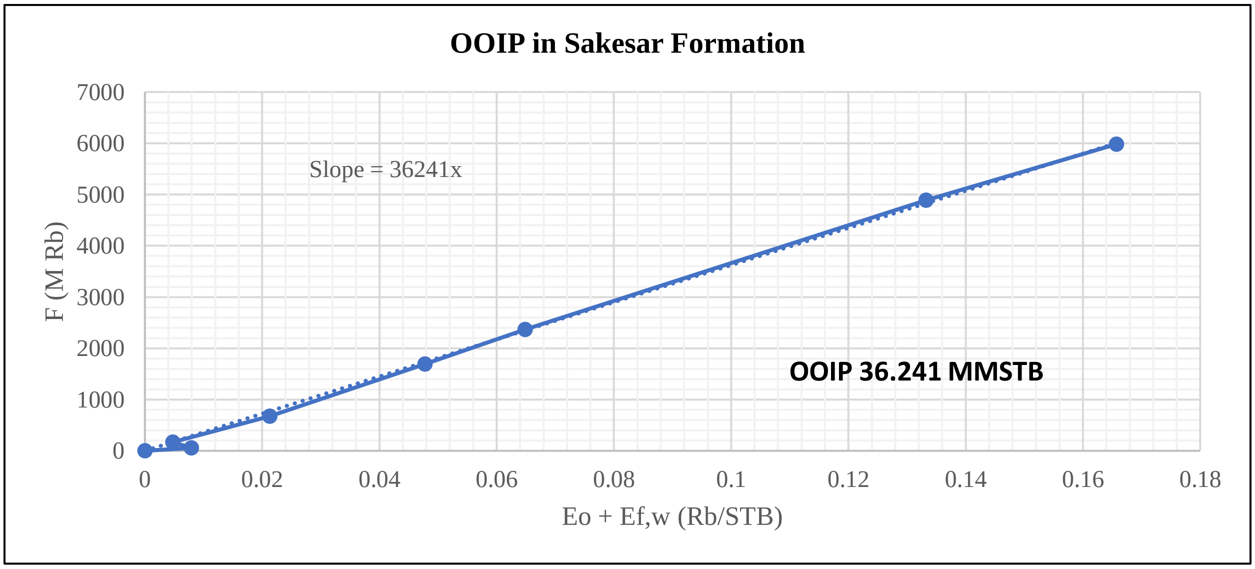

Figure 14 OOIP Sakesar

Table-6 represents the all estimated OOIP for sakesar formations.

Table 6 Sakesar OOIP from different C_f Values

S.no	Assumed C_f (1/psi)	OOIP (MMSTB)	GIP (BCF)
1	5.0×10^{-6}	36.241	35.842
2	7.44×10^{-6}	33.967	33.593
3	1.0×10^{-6}	31.869	31.518
4	2.0×10^{-6}	25.67	25.388
5	2.5×10^{-6}	23.394	23.137
6	3.0×10^{-6}	21.488	21.252
7	4.0×10^{-6}	18.477	18.274
8	5.0×10^{-6}	16.205	16.027
9	6.0×10^{-5}	14.431	14.272
10	7.0×10^{-5}	13.007	12.864

4.1.2. OOIP in Chorgali

Formation compressibility of Chorgali is not known precisely. Different values of C_f from 5.0×10^{-6} to 50×10^{-6} /psi were assumed to calculate OOIP in the chorgali reservoir, Table 7 summarized the range of OOIP in the range of 1.591 MMSTB to 7.198 MMSTB and GIP in the range of 1.723 MMSCF.

Table 7 OOIP Chorgali

S.no	Assumed C_f (1/psi)	OOIP (MMSTB)	GIP (BCF)
1	5.0×10^{-6}	7.198	7.799
2	7.44×10^{-6}	6.06	6.566
3	1.0×10^{-5}	5.173	5.604
4	2.0×10^{-5}	3.311	3.587
5	2.5×10^{-5}	2.805	3.039
6	3.0×10^{-5}	2.434	2.637
7	4.0×10^{-5}	1.924	2.084
8	5.0×10^{-5}	1.591	1.723

4.2. Water Breakthrough

Buckley-Leverett Displacement Mechanism has been used to predict the water breakthrough time for a reservoir in the field. The following properties were used for the reservoir i.e. water saturation, oil and water relative permeability, porosity, oil viscosity, and water viscosity. Oil is displaced from a rock by water as the fluid is displaced from a cylinder by a leaky piston. This theory is based on the relative permeability concept.

The distance between the injector well and the producer well is 2.5 kilometre. The sensitivity analysis determined the width of the swept reservoir and thickness of the swept bed. Water injection was started in March 1996, in response to water injection, oil production started to increase in producing well just after four months of water injection.

The breakthrough time was estimated as 810 days with the average oil production rate of 3260 bbls/day attaining oil recovery of 2.64 MMSTB form the start of water injection at and breakthrough occurring at producing.

4.3. Model Initialization:

At the present, field XYZ is on water flooding and secondary aquifer have been generated in the reservoir. About 25 million barrels of water have been injected and 13.7 MMbbls of oil have been recovered. It is important of this research work to produce storage space in the reservoir for CO_2 emissions injected through the course of the project, and also to determine the bypass oil in the reservoir that needs to be recovered through EOR. All simulation work performed on Schlumberger ECLIPSE Reservoir Simulator as this simulator has also been used by the company staff.

4.3.1. CO_2 Gas Injection Rates

Three different gas injection rates were proposed to implement underground geological sequestration of carbon emissions into this depleted oil field, the three different CO_2 injection rates on which comparison is made are illustrated in (Table 8)

Table 8 CO_2 Injection Rates

Cases	**CO_2 Injection Rate (MMSCF/Day)**
Case-1	5
Case-2	10
Case-3	20

4.4. Base Case Simulation

Base Case Simulation starts from the time of field discovery and production forecasted till the end of the year 2035. Reservoir model of this selected field is a fractured carbonate reservoir, comprises of 3 layers and has 7,500 grid cells. The reservoir has lower matrix Porosity but very high matrix permeability in fractured regions. The producing wells (Fim 1, Fim-2) are producing wells, while well (Fim-3) is the water injection well which was used for reservoir pressure maintenance during secondary recovery in later part of the production stage of this field.

4.4.1. Reservoir Pressure Analysis

The site selected for geological storage of CO_2 emissions was depleted field so it was obvious that reservoir pressure of the selected field would be at a declining rate. The analysis for reservoir pressure history of the base case model before injecting CO_2 into the reservoir was important because the injected CO_2 fluid will have effect on reservoir pressure once injection takes place in this field. The analysis includes a 3D model of reservoir showing pressure values at start and end of the simulation without injecting CO_2, and reservoir pressure curve showing the overall history of reservoir pressure from the time of field discovery to end of the simulation result.

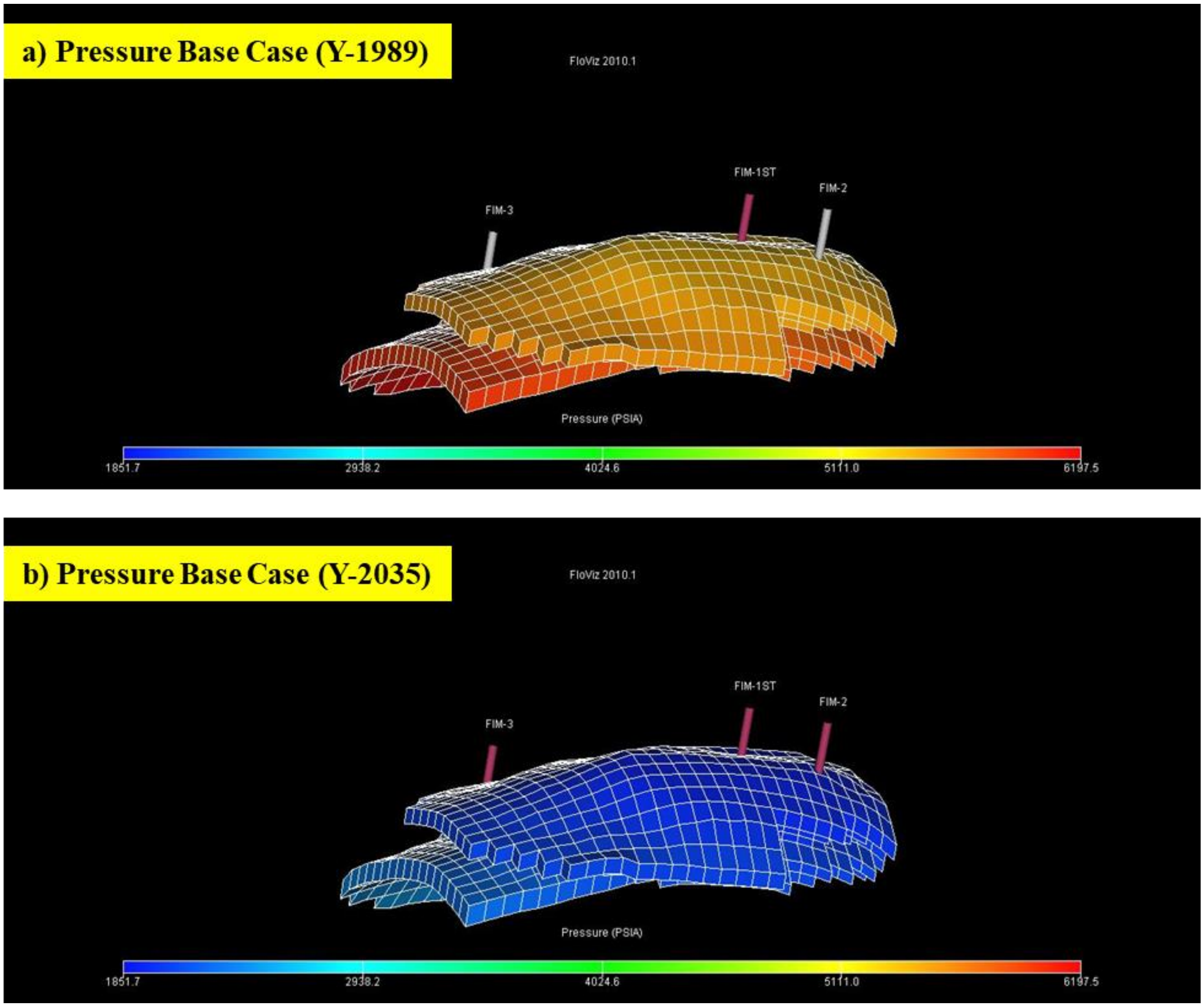

Figure 15 (a) Pressure in Base Case (1989) (b) Pressure in Base Case (2035)

The result in Figure 15(a) show reservoir pressure value of 5910 psi at the time when field started producing hydrocarbon resources (1989), while in Figure 15(b) shows the reservoir pressure become as low as 2,160 psi, and during this phase, the reservoir was also subjected to water injection.

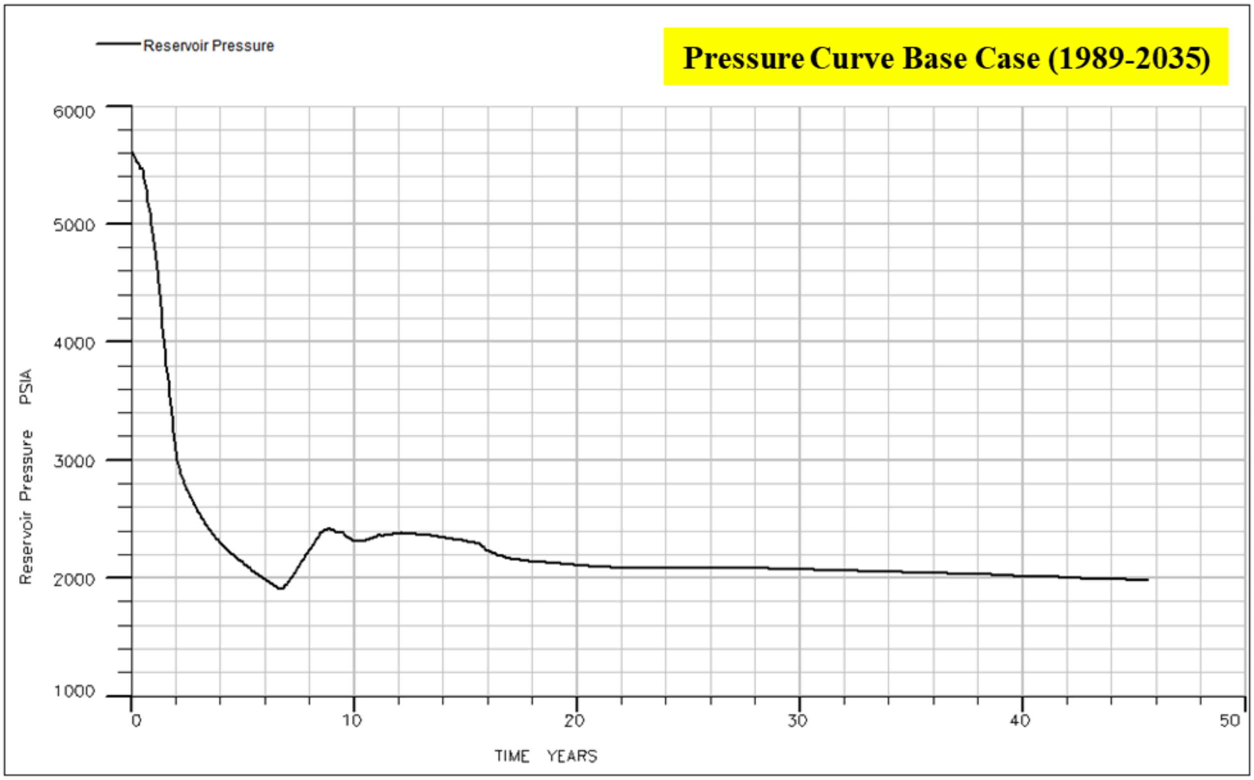

Figure 16 Pressure Curve Base Case

The Figure 16 illustrates the reservoir pressure of base case model started to decline in its early stages and reached as low as 1934 psi, only pressure surge seen in the result was due to water injection, and the pressure was stable to 3,224 psi for some time and then again started to decline reasonably. The constant pressure line for the rest of the simulation period indicates no change in reservoir pressure unless any pressure maintenance technique applied during this period.

4.4.2. Oil Saturation Analysis

For determining the future course of actions of any oil field, it is important to measure the gross volume of fluid occupied by a rock in subsurface. The site selected for CO_2 emissions was water drive with reservoir already implemented with water flooding, oil saturation of reservoir ranges from average oil saturation to low values, where the majority of saturation occupied by water. The analysis includes the comparison of oil saturation values of reservoir model between the time of field discovery (1989) to end of simulation result (2035)

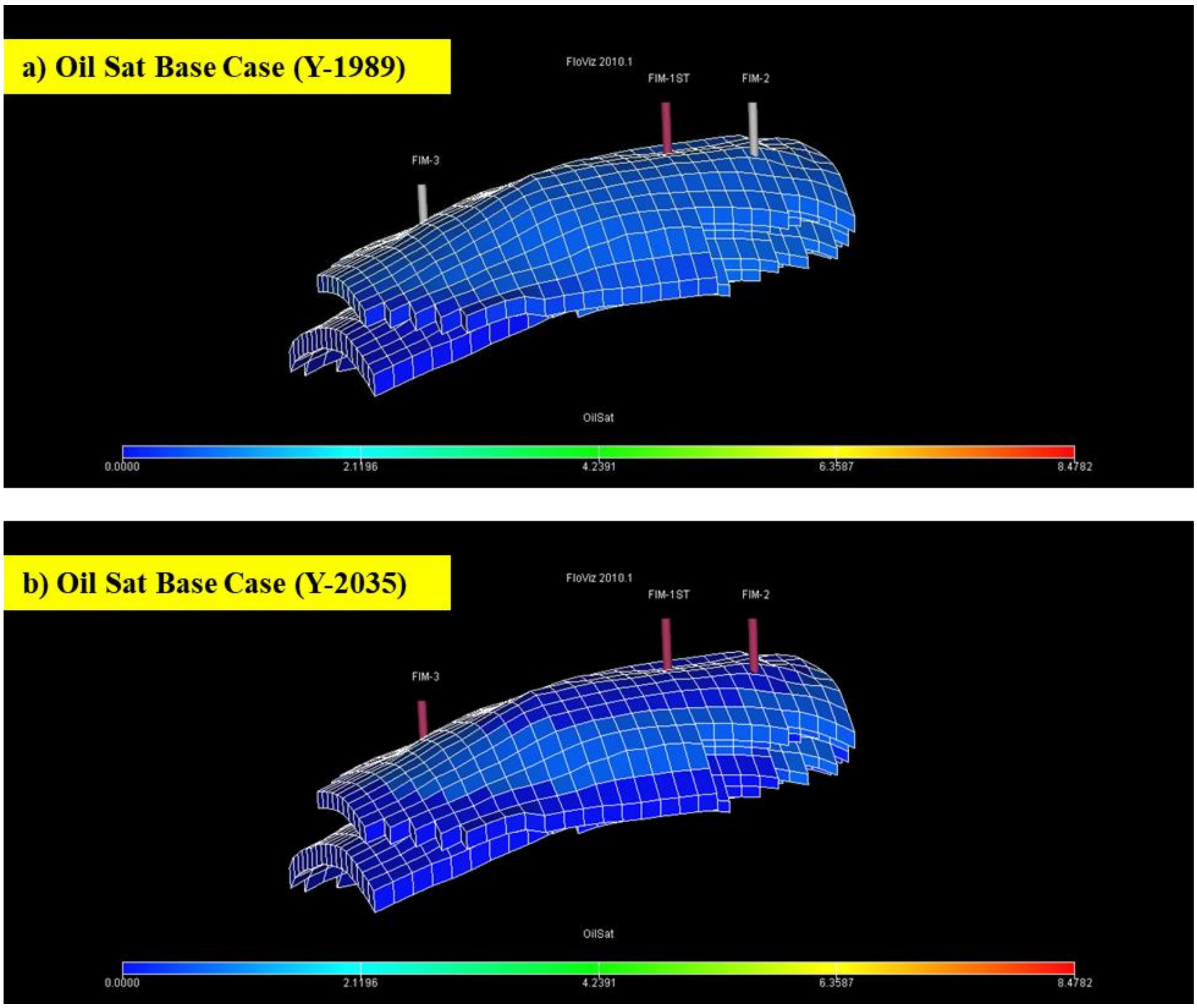

Figure 17 (a) Oil Saturation in Base Case (1989) (b) Oil Saturation in Base Case (2035)

Figure 17(a) demonstrates a fraction of oil occupied by reservoir as oil saturation value found as 0.57 at the start of field recovery in the year (1989), while Figure 17(b) shows oil swept out in a lower portion of the reservoir and has extreme low values of oil saturation, but in middle and upper portion of reservoir still some volume of oil remains, and typically recovery of oil in those available portions is relatively difficult due to the fractured structure of the reservoir.

4.4.3. Oil Production Rate Analysis

The site selected for storing CO_2 emissions came on regular production in October 1989, at the high oil production rate of 4000 bbl/day, after continuous production for six years, reservoir pressure declined to below bubble point pressure and consequently oil production declined from 3800 to 1800 bbl/day, with water injection implemented in the year 1996, oil production again reached at 3800 bbl/day, after continuous water injection for two years water breakthrough occur and oil production declined to merely 350 bbl/day.

The oil production rate analysis includes a graph showing the overall history of oil production rate and a graph showing the relation of oil production and water production.

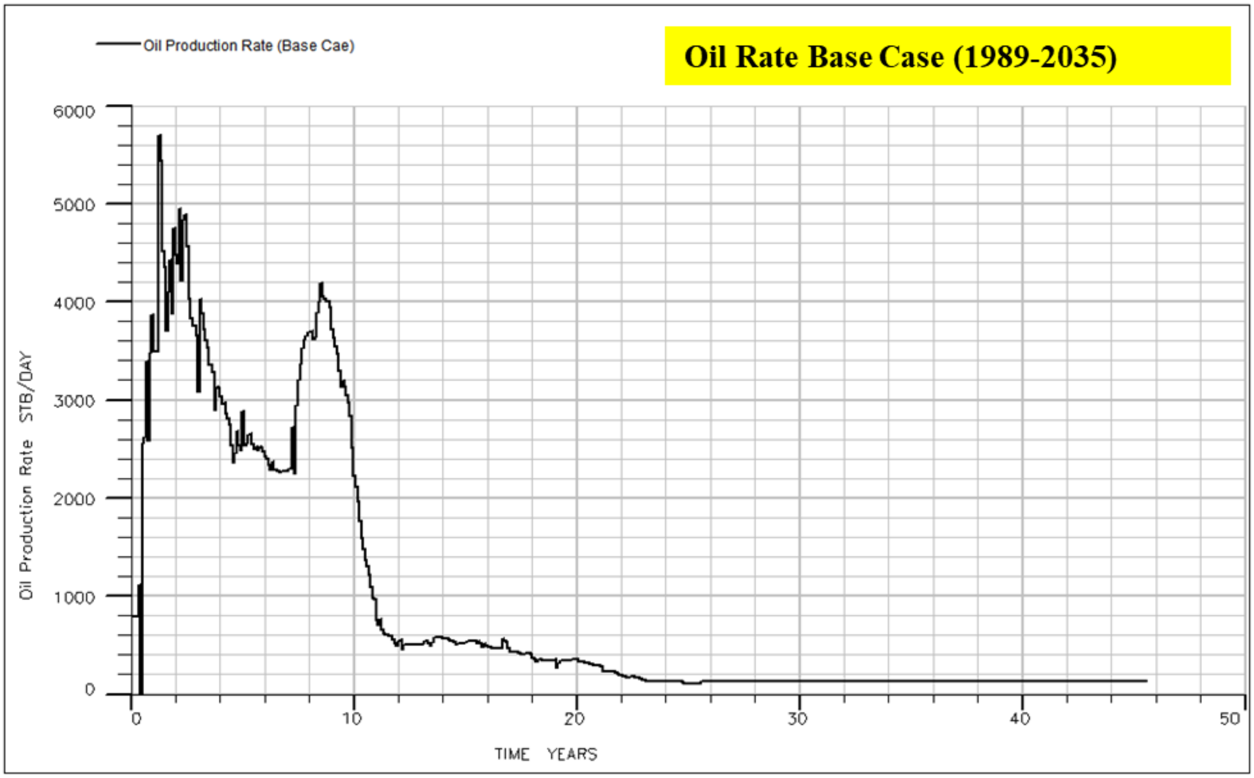

Figure 18 Oil Rate (Base Case)

Figure 18 displays oil production rate of the existing base, selected field during its early years produced oil at good rate, the highest peak shows field produced 5,800 bbl/day best in the year 1990, and then field lost its high oil production rates. The stable line shows future forecast and no change in production rates

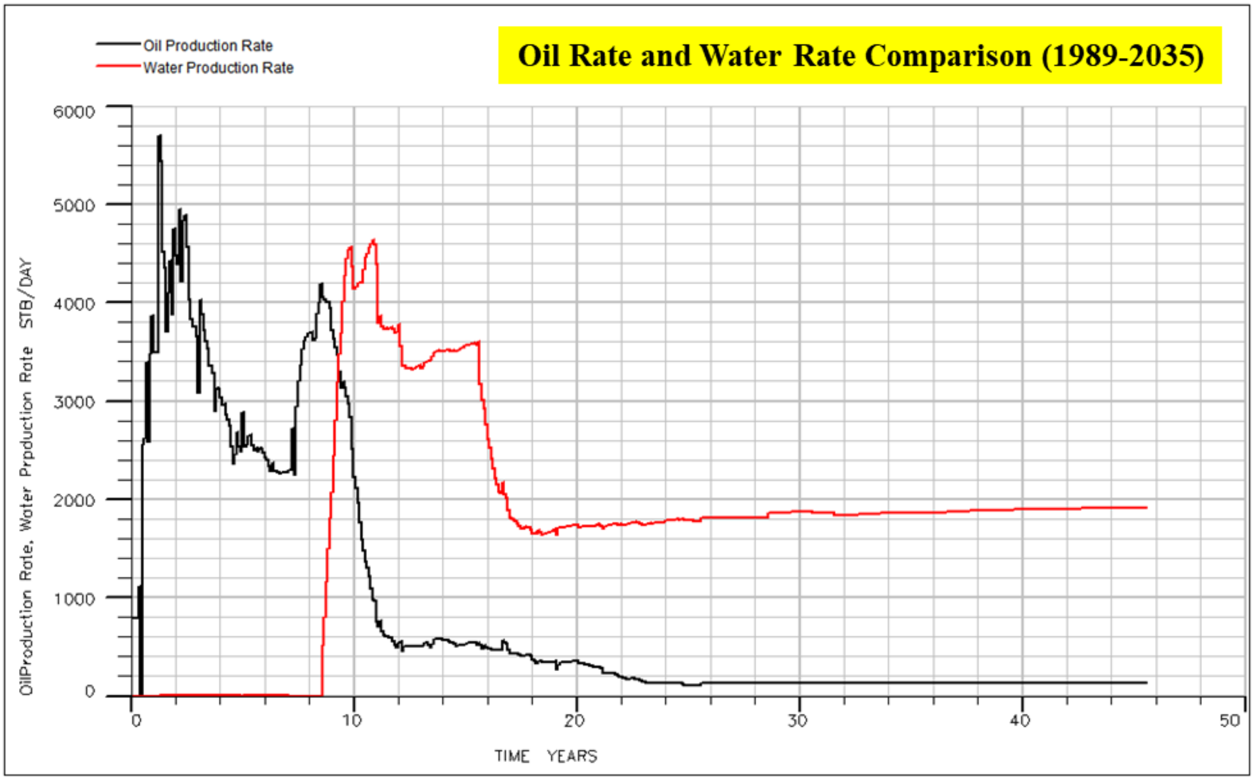

Figure 19 Comparison of Oil Production and Water Production

The Figure 19 demonstrates the effect of water production on the reservoir oil production rate. The distance between the water injection well and primary producing well was 2.5 Km when operators observed the increase in oil production rate and reservoir pressure earlier during water injection, they started injecting water at high rate of 4000-4500 bbl/d, which not only breakthrough water in producing zones, but also halted the oil production as shown clearly in graph. The moment the breakthrough occurs and water production went up oil production rate started to decline.

4.5. Reservoir Model with CO_2 Injection

The actual base case model has three wells, two producing (one each for producing formation) and one water injection well which has been used for water injection since secondary stage recovery of this field. It was obvious to add another well on the structure of reservoir for CO_2 gas injection, and the position selected for the new injection well was considering the distance between producing wells, and higher oil saturation of oil in that region. The new CO_2 injection well was programmed to start injecting CO_2 from 1 Jan 2015 and performance forecasted till the end of the simulation year 2025.

The main objective of this research work is to explore the opportunity for underground geological sequestration of CO_2, but once CO_2 gas injection started in the field, other effects also need to be analysed observe the performance and quality of CO_2 injection operation.

These effects are,

- Effect of CO_2 injection for underground geological storage of CO_2 emissions
- Effect of CO_2 injection on reservoir pressure maintenance
- Effect of CO_2 injection in improved gas recovery
- Effect of CO_2 injection in improved oil recovery (EOR)

4.5.1. Effect of CO_2 injection in underground geological storage of CO_2 emissions

There are many alternative options to reduce CO_2 emissions form atmosphere, like storage of CO_2 emissions in the ocean, injecting CO_2 in deep coal mines or deep saline aquifers. The concept of underground geological storage in depleted oil field was preferred because it offers the potential to store a significant volume of CO_2 emissions [1]. CO_2 storage in deep oil reservoirs is still best options for storage sites because the existing infrastructure of injection of oil facilities may be utilized and there is always a possible opportunity for additional recovery of oil where CO_2 injection may have economic value [2].

a) Geological Storage (CO_2 Injection at 5 MMSCF/day)

The CO_2 gas injection starts from 1 Jan 2015, which is the simulation start date for CO_2 injection, and at the constant injections rate of 5 MM SCF/day, the overall total underground geological storage of CO_2 until year 2025 estimated to be 9.03 Billion Cubic feet (BCF).

b) Geological Storage (CO_2 Injection at 10 MMSCF/day)

At the constant injections rate of 10 MM SCF/day, the overall total underground geological storage of CO_2 until year 2025 estimated to be 9.308 (BCF).

c) Geological Storage (CO_2 Injection at 20 MMSCF/day)

At the constant injections rate of 20 MM SCF/day, the overall total underground geological storage of CO_2 until year 2025 estimated to be 9.71 (BCF

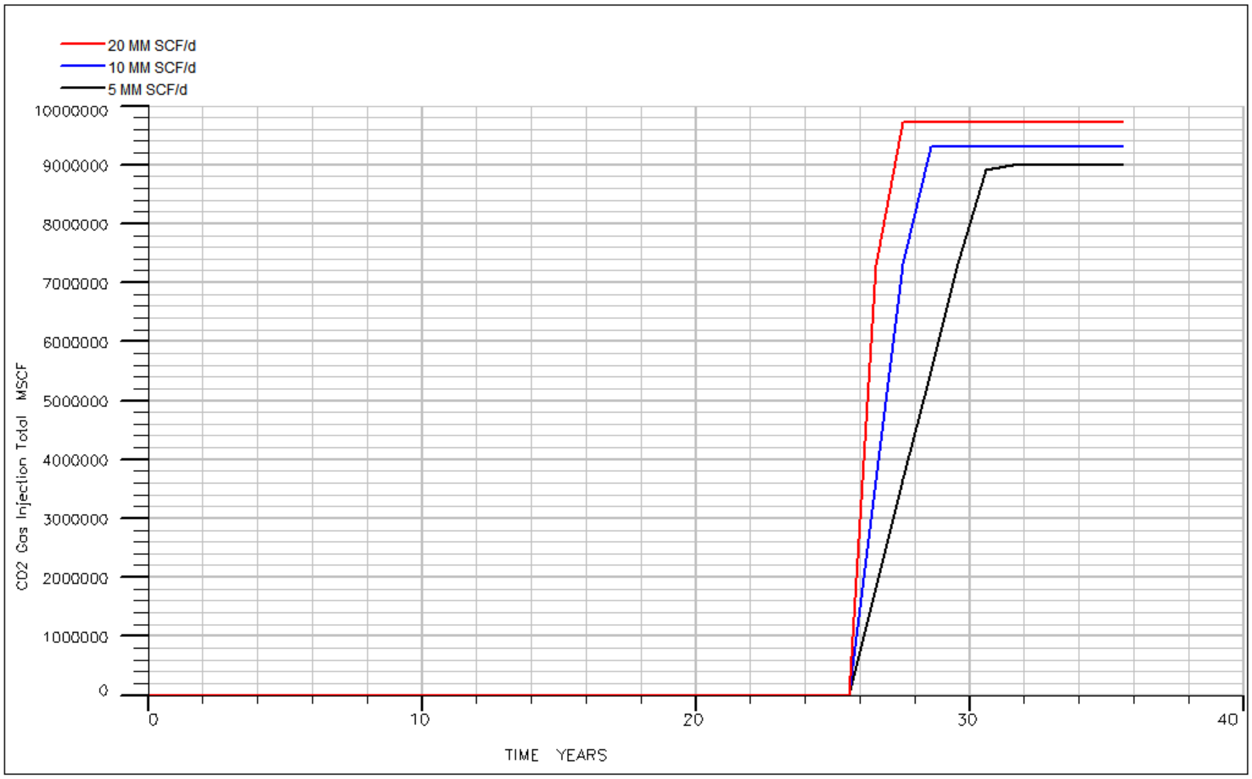

Figure 20 overall CO_2 Injection Total

The Figure 20 result is the comparison of all three cases with three different injection rates of CO_2 injection, it illustrates the field started injecting CO_2 for underground geological sequestration of CO_2 emissions, the immense volume of CO_2 gets stored under the vicinity of the reservoir. CO_2 is hazardous gas and it is always desirable for any CO_2 injecting operation to store maximum amount CO_2 gas under geological storage.

4.5.2. Effect of CO_2 Injection on Reservoir Pressure Maintenance

Many techniques have been developed where it is possible to evaluate pressure maintenance of reservoir through CO_2 injection into the depleted field [3]. CO_2 injection allows reservoir pressure maintenance and re-pressurization of the reservoir, when pressure gone below bubble point pressure. The CO_2 gas in the supercritical state having higher density and viscosity tends to have much higher-pressure diffusivity than molecular diffusivity, hence making re-pressurization of reservoir much faster than molecule diffusion [4].

a) Pressure Maintenance (CO_2 Injection at 5 MMSCF/day)

As experienced earlier in the base case simulation that reservoir pressure declined consistently right after the breakthrough of water. This CO_2 injection technique tends to increase reservoir pressure of 2093 psi (2015) to 5905 psi (2025).

b) Pressure Maintenance (CO_2 Injection at 10 MMSCF/day)

Increases reservoir pressure up to 5,998 (2025)

c) Pressure Maintenance (CO_2 Injection at 20 MMSCF/day)

Increases reservoir pressure up to 6584 psi.

The Figure 21(a,b,c) are the 3D model of the reservoir illustrating behaviour of reservoir in post injection of CO_2 behaviour at end of simulation time, and it has been observed by looking at the result that CO_2 injection has allowed reservoir of this depleted oil field to be re-pressurized and pressure maintenance through different injection rate of CO_2 has been achieved.

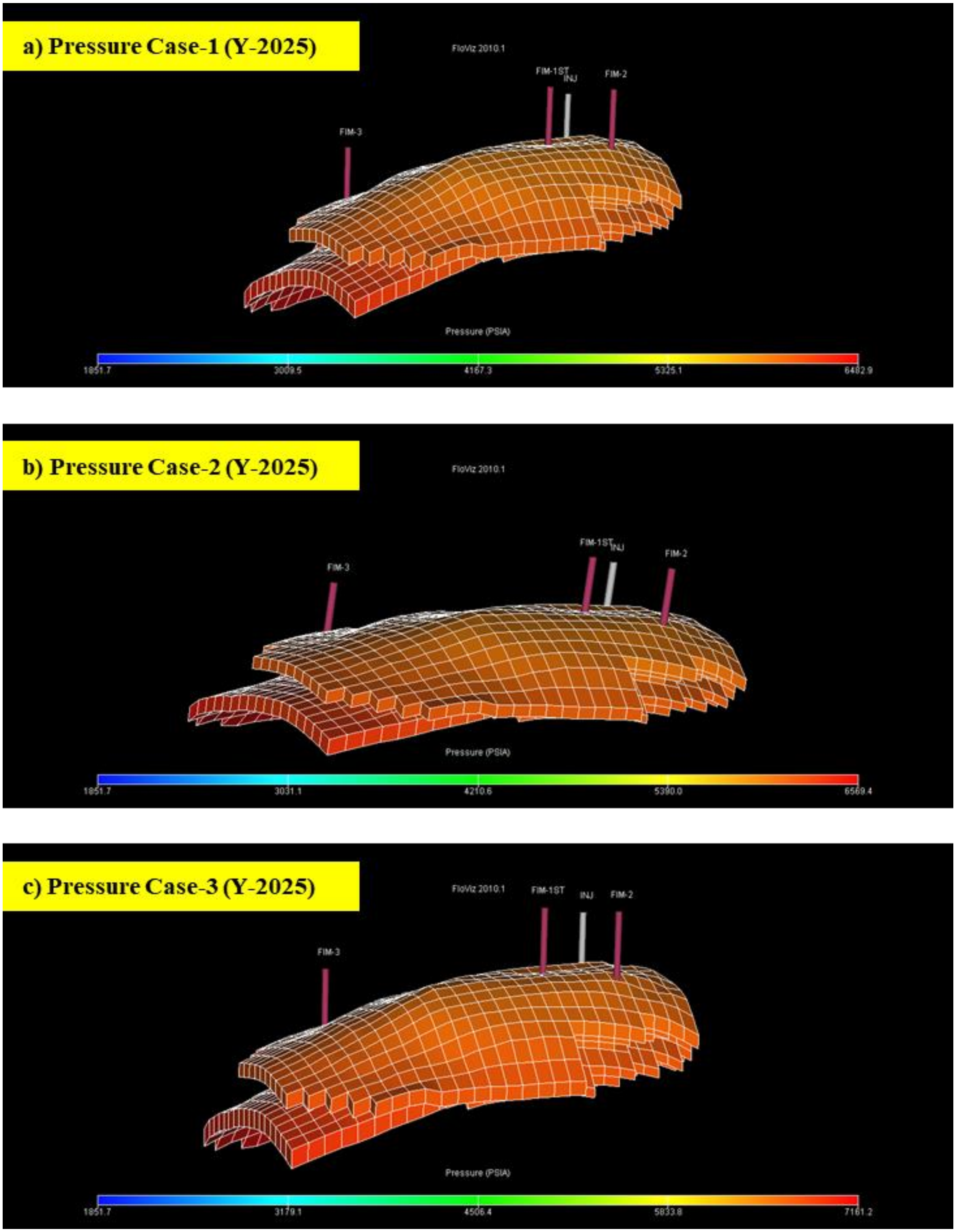

Figure 21 (a) Pressure at Injection Rate of 5 MM (b) Pressure at Injection Rate of 10 MM (c) Pressure at Injection Rate of 20 MM

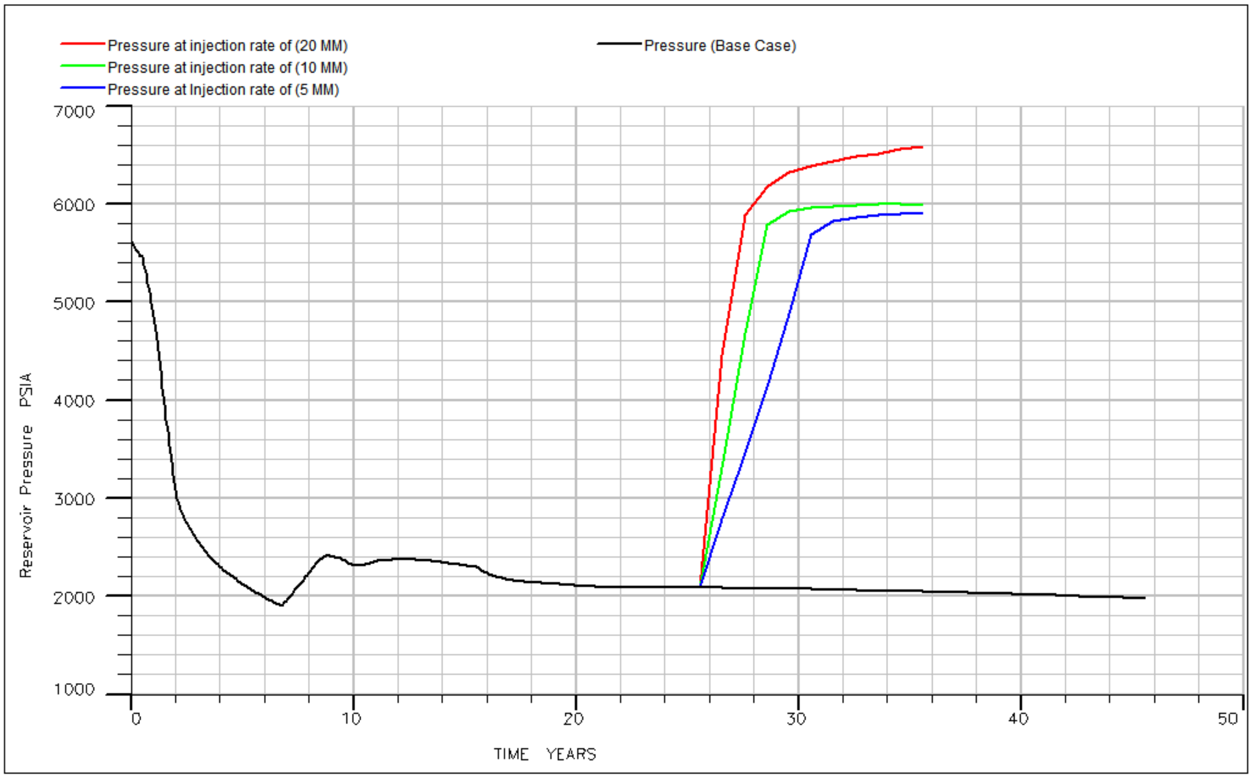

Figure 22 Pressure Comparison

Figure 22 is the comparison result of base case reservoir pressure with all three cases of different injection rates of CO_2. The comparison shows reservoir pressure started to increase right from the time of injection, and three curves of different injection rates reach a different higher value of pressure point with respect to its injection value. The base case curve extrapolated till the year 2035 and hence still goes with low pressure and gives no sign of pressure maintenance.

4.5.3. Effect of CO_2 Injection on Improved Gas Recovery

In addition to the additional oil recovery and pressure maintenance, CO_2 injection has also been commercially applied for additional gas recovery particularly in countries like the USA, Brazil, and Canada [5]. Recovery of coal bed methane through injection of CO_2 is proven method but there is lack of research done on the recovery of gas from depleted oil zones by CO_2 injection, mainly because of the reason of already high recovery of gas recovery through conventional methods [6].

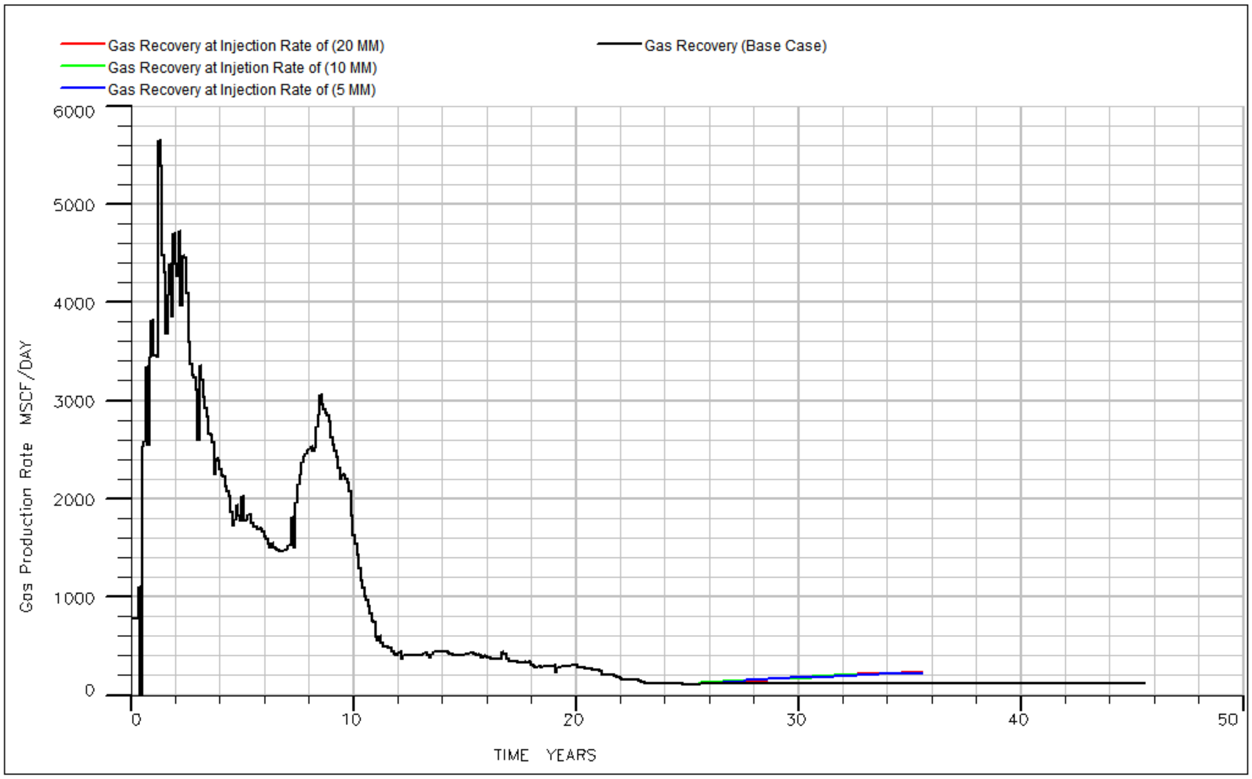

Figure 23 Improved Gas Recovery

The gas of hydrocarbon in nature is also a very important commodity of interest and has very good economic value when it produced in bulk. Figure 23 shows in earlier days of base case recovery, gas produced in commercial quantity but as the field depleted with lower pressure the gas production also declined. While implementing CO_2 injection there is a visible difference observed of additional gas recovery which usually resulting from different CO_2 injection rate and comparison been made with the base case scenario. While Figure 24 displays the comparison of total production of gas with the base case, by looking at these production values of gas recovery, it cannot be taken as commercial values as the peak value for gas produced reaches 0.23 MM SCF/day when injecting CO_2 gas at an injection rate of 20 MM SCF/day, but still the effect of CO_2 injection on the base case model can be observed with slightly additional recovery of gas.

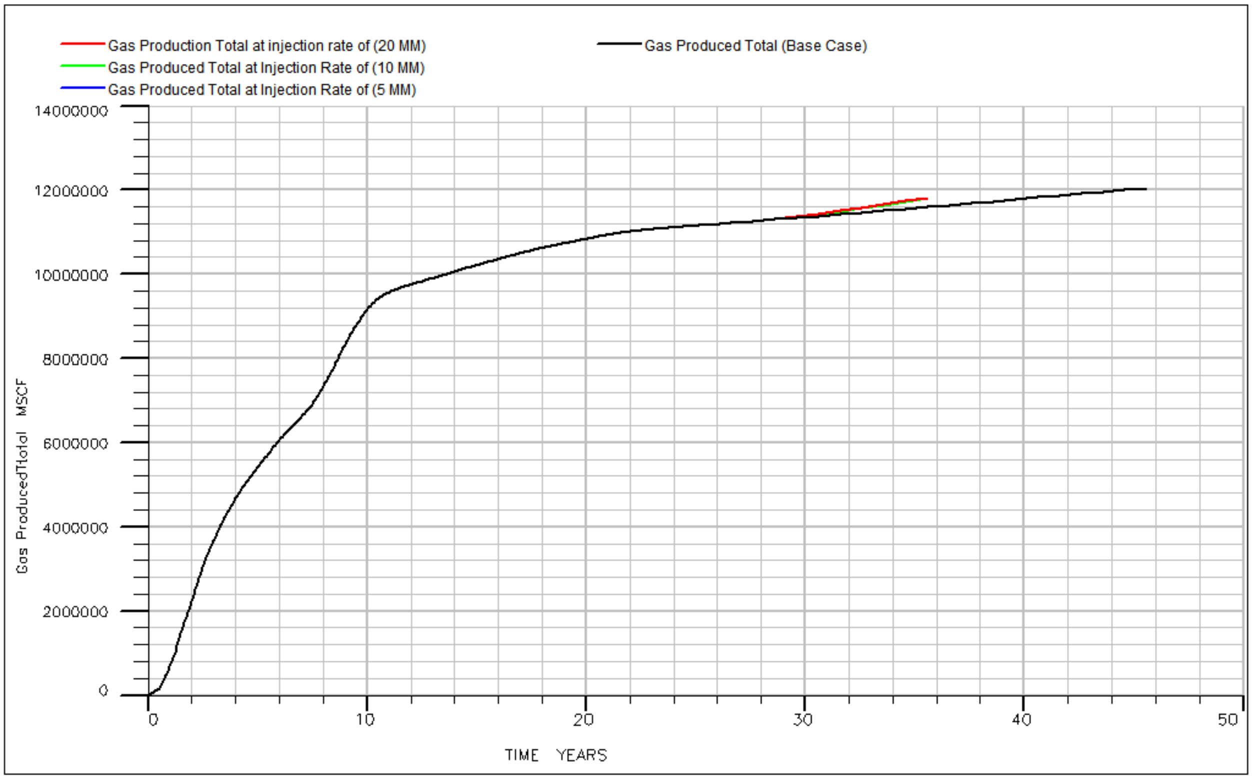

Figure 24 Total Gas Recovery

a) Gas Recovery (CO_2 Injection at 5 MMSCF/day)

Total gas produced at end of the simulation result was 11.805 BSCF and at on the same date base case total gas production was 11.6 BSCF, hence recovers additional 205 MMSCF of gas recovery over the life of the project.

b) Gas Recovery (CO_2 Injection at 10 MMSCF/day)

Recovers additional 203 MMSCF of gas recovery over the life of the project.

c) Gas Recovery (CO_2 Injection at 10 MMSCF/day)

Recovers additional 220 MMSCF of gas recovery over the life of the project

4.5.4. Effect of CO_2 Injection on Improved Oil Recovery (EOR)

CO_2 capture and underground geological sequestration of CO_2 emissions can lead to high volume reduction of CO_2 emissions, and when such emissions in form of supercritical CO_2 fluid injected into depleted oil and gas reservoirs which may result into additional oil recovery from fields also called (CO_2-EOR) [7]. This research focuses on injection of CO_2 gas in fractured carbonate reservoirs for geological sequestration of CO_2 emissions, and carbonate reservoirs are usually characterized with low permeability but relatively high permeability in selected fractured zones causing a significant amount of CO_2 storage and additional recovery of oil [8]

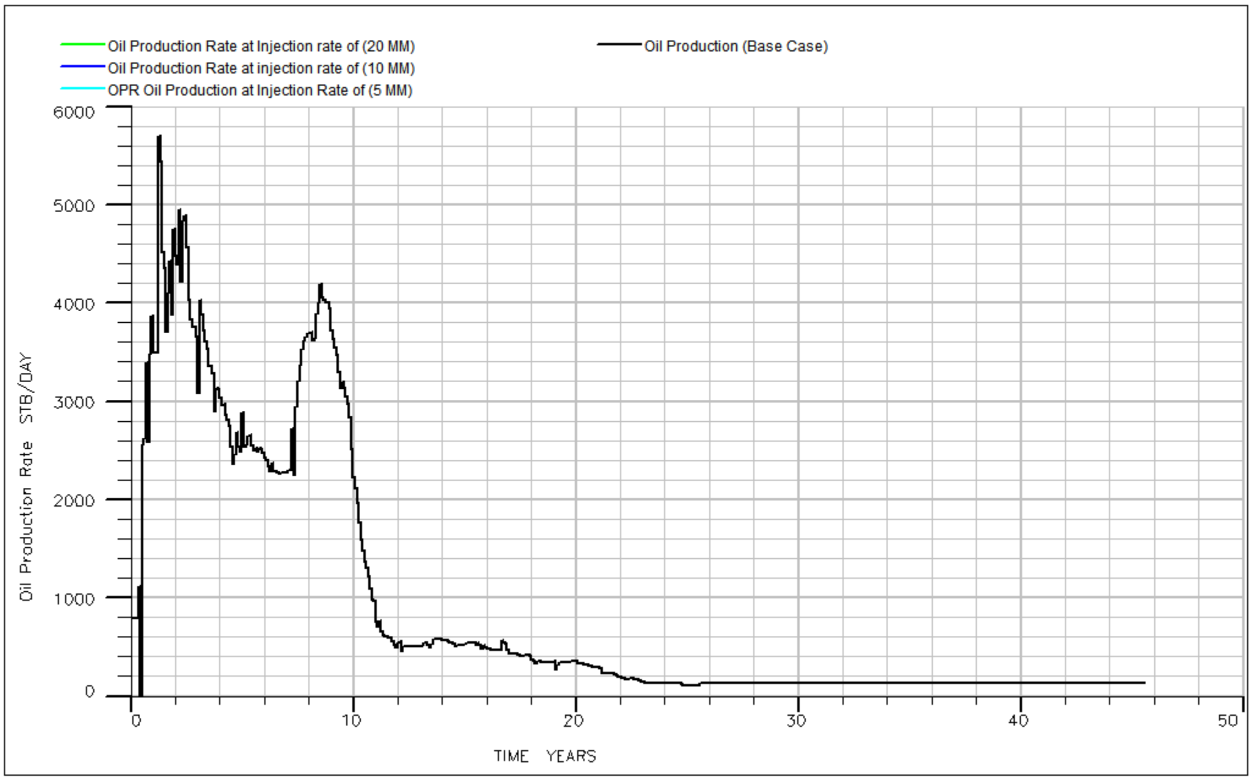

Figure 25 Comparison of Oil Production Rate

The Figure 25 gives a glimpse of comparison of oil production rate of base case with three different rate of CO_2 injection. Results show there is no improved in oil recovery (EOR), and it seems right from the start the base case oil production rate goes parallel with oil production rates of all other three cases with CO_2 injection. When looking out closely in the simulator zooming setting, it shows after some period of time from the date when the CO_2 injection period starts, additional oil starts to recover and then again rate comes in parallel line with base case curve, that additional oil recovery range in between marginal 13-16 bbl, where higher value of this range is obviously for the higher injection rates, but this difference of recovery is very little when scope of the project is so big and higher risk is involved for such project.

When studying the previous history, structure, and geology of this field, the following reasons are the maybe some of the reasons behind in no any additional recovery of oil [9]

Water Breakthrough: While the decline in reservoir pressure water injection started with a maximum rate of 85000 bbl/day for pressure maintenance, following water injection oil production increased but after two years water breakthrough occurs with 80% water cut and oil production declined from 3800 bbl/day to 350 bbl/day at that time.

Fracture Mechanics: The sudden increase in the oil production during water production was attributed to oil in a fracture that was pushed by injected water that time, hence as there is no oil remains in the fracture region resulted to no oil recovery via CO_2 injection.

High Permeability Values: The oil production of this field mainly depends on the permeability of fractured region of reservoir, the high permeability of 4200 md makes it difficult for any injecting fluid to attain desire minimum miscible pressure.

The Figure 26 below might validate the above-given arguments, it explains the excessive water production observed for all cases of different injection rates, which halted the oil and gas production rates to the considerable limit. The base case did not have much higher water production even during water injection, but water breakthrough in earlier stages of this field made room for such excessive production of water even when gas streams are injected in the injection well.

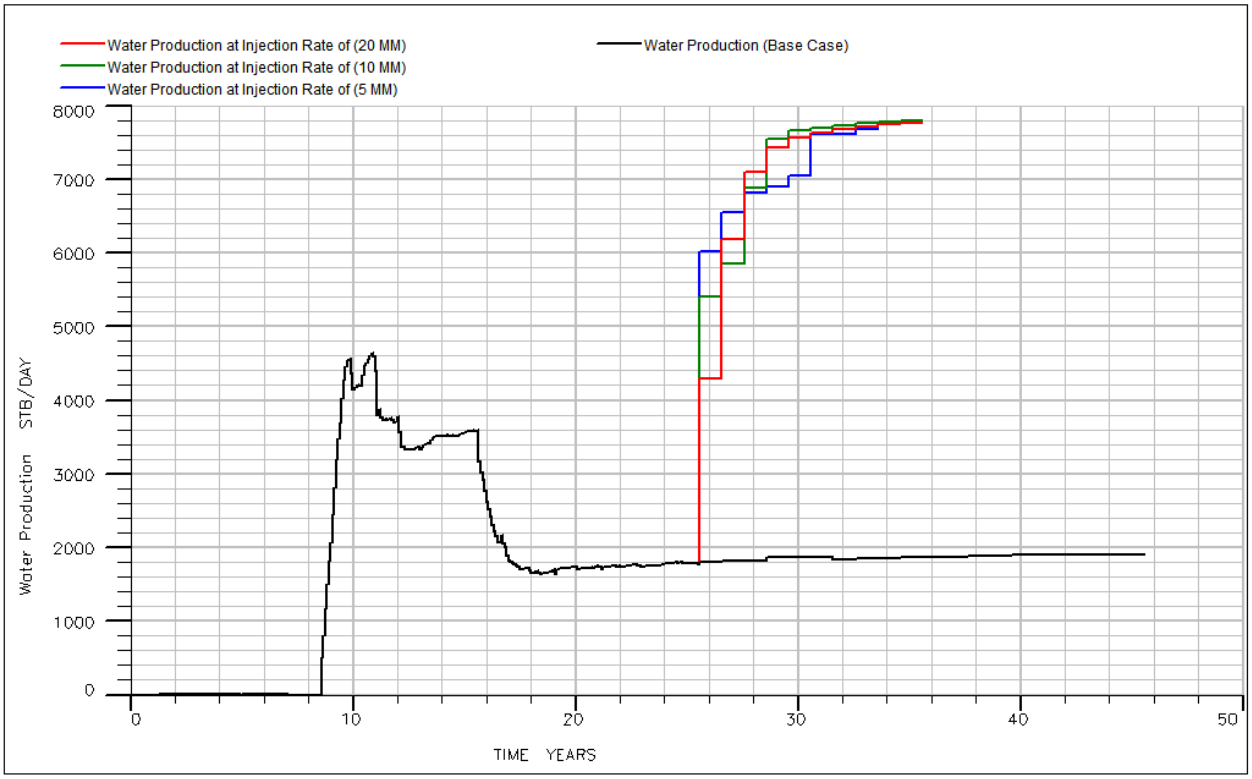

Figure 26 Comparison of Water Production

4.6. Comparative Statement

Table 9 summarizes all the results of this research and let it also compare with the base case model.

Table 9 Comparative Statement

		CO_2 Injection at Rate of (at end of the year 2025)		
Parameter	**Base Case (at the end of Year 2025)**	**5 MMSCF/day**	**10 MMSCF/day**	**20 MMSCF/ day**
CO_2 Storage	9.03 BCF Total	9.03 BCF Total	9.308 BCF Total	9.71 BCF Total
Reservoir Pressure	2120 psi	5905 psi	5998 psi	6584 psi
Oil Production	14.48 MMSTB	14.47 MMSTB	14.482 MMSTB	14.486 MMSTB
Gas Production	11.6 BSCF	11.80 BSCF	11.80 BSCF	11.82 BSCF
Water Production	1810 bbls/day	7797 bls/day	7790 bbls/day	7756 bbls/day

4.7. Economic Analysis Framework of CO_2-EOR:

4.7.1. Storage and Sequestration Cost

In CO_2-EOR operation the significant amount of cost spends on sequestration of CO_2, and as suggested by [10] the following costs bear the major chunk of cost for CO_2 sequestration in CO_2-EOR.

CO_2 Capture and Compression Cost: This involves a high portion of the cost in CO_2 sequestration system because it involves both dehydration and hence it also regarded as the high energy-intensive process and require more cost. If the low-pressure CO_2 stream is long enough entering the compressor its compression cost will be lower but has higher compression cost for small CO_2 flow stream. Estimated compression range starts from USD 7.4 to 12.4/tonne [11]. Apart from compression, another big concern in sequestration technology is a high cost for capturing CO_2 which amounts for as high as 75% of the total cost for CO_2 sequestration, this high cost is also the reason that technology has not become prominent worldwide as it should be for the future generation. The high cost of capturing CO_2 depends on many factors like capturing a large amount of CO_2 gas and process through CO_2 gas is captured be it chemical or physical.

Transportation Cost: Gases are meant to be transported via pipeline which is always the recommended mode of transportation in major operations, while tankers and ships are the best options to transport CO_2 from one end to another end oversea. Some properties and gas characteristics need to be considered while estimating transportation cost of CO_2 via pipeline, as these properties vary depending on project location, CO_2 capture source, and properties of CO_2. Some other factors like pipeline design, the terrain should also be taken into consideration due to which cost may increase considerably. As stated in [12] on the average transportation cost of CO_2 is around USD 21 per inch of pipeline diameter per Km of length. This price may vary depending on terrain site location and terrain characteristic.

Storage Cost: Storing CO_2 geologically underground requires drilling of injection well, which not only accounts for huge cost but also great technical expertise. Cost for drilling injection well varies as it depends on parameters like depth of reservoir for storing CO_2, formation temperature, location, reservoir radius and cost for the drilling rig and other equipment's used for drilling injection well. Offshore underground CO_2 storage is more expensive as offshore drilling well is a more complex operation. As pointed by [13] depending on parameters mentioned above Cost for underground CO_2 storage range from way below to USD 5 to high above USD 20 per ton.

4.7.2. Cost of CO_2 Storage for EOR Operation

The cost of the CO_2 flood is calculated on the modelling and assessment of the CO_2-EOR performance and complex interaction between the recoverable oil and injected gas. But in some cases, generalized cost assumed by using the rule of thumb. To use this rule EOR process must be split into a number of steps, EIA report [14] is used for calculation field and operating costs based on three cases, Table 10 represents the results of the cost and all the description, steps for CO_2 storage in EOR operation are illustrated as follows,

First: how much amount of oil recovered for CO_2 mass flow rate using CO_2 effectiveness factor, the CO_2 effectiveness factor is taken as 150 scm (5300 ft^3)

Second: on average what amount of enhanced oil produced from a single production well, (here assumed average taken as 40 bbl/well)

Third: To calculate the number of injection wells by the ratio of the producer to injector 1 to 1.1

Fourth: Determination of capital cost of CO_2 recycle plant on recycling CO_2 at ratio 3 by power plant.

Table 10 Economic Effectiveness Parameters

Parameter	EOR Base Case	EOR (High Cost)	EOR (Low Cost)	Unit
Effectiveness of CO_2	150	220	70	scm/bbl enhanced oil
Oil Production/Well	40	27	75	bbl oil/day/well
Max: Recycle Ratio	3	4	1	
Crude Oil Price	45	12	70+	$/bbl
Waterflooding	Yes	No	Yes	
Levelized Annual CO_2 Net Storage Cost	14.5	(76.5)	(93.4)	$/tonne CO_2

Oil reservoirs worldwide are considered a great place to store bulk amount of CO_2, where the main goal is to produce extra oil as possible form depleted field oil fields by CO_2 flooding in a CO_2-EOR operation. These oil reservoirs are also considered very safe for CO_2 storage, to-date no oil field site has been directly monitored for CO_2 sequestration.

4.7.4. Implementation Financing

If the project is able to pay for itself from increased oil production. The expected increase of oil production through the implementation of EOR will generate additional reserves, also yield additional oil recovery. With 7-9 Million barrels still to be recovered, potential revenue at $ 40/BBL is expected to be above $ 250 Million [15]. Capital for the project will be provided by the operating company on a self-financing basis.

4.7.5. Capital Cost Estimates

Cost of the CO_2-EOR project is expected to approach $12-15 million [16]. This is not out of proportion to the cost of exploring, drilling, developing, and gathering oil from a new domestic oil field, so CO_2-EOR cost is economically justified. If successful, CO_2-EOR concept could be rolled out to the 15 fields in Pakistan now under consideration, as well as being applied to at least 10 new fields. Total rollout potential, then, for approximately 25 fields, would approach $300 million.

4.8. Summary

The field selected for underground geological sequestration was located in Potwar region of Pakistan and it has two-producing formations and has very low matrix porosity due to which volumetric technique was not considered for reserve estimation and Materia Balance determines 35.55 MMSTB of total reserve estimation in both formations, hence the idea was also to target these untapped reserves for additional recovery of oil. Reservoir Modelling was performed by ECLIPSE Reservoir Simulator, 10-year simulation results show that depleted oil field has the potential to store more than 9 BSCF of CO_2 gas emissions, reservoir pressure increased significantly right after the time of CO_2 gas injection, but there was no major change observed in improved oil production when compared to previous base case, however, minor improved gas recovery was observed.

4.9. References

[1] P. Roefs, M. Moretti, K. Welkenhuysen, K. Piessens, and T. Compernolle, "CO_2 -enhanced oil recovery and CO_2 capture and storage: An environmental economic trade-off analysis," *J. Environ. Manage.*, vol. 239, no. November 2018, pp. 167–177, 2019.

[2] S. J. Lu, L. J. Gao, Q. F. Li, X. Han, and D. Y. Zhao, "On-line monitoring technology for internal corrosion of CO_2 -EOR oil field," *Energy Procedia*, vol. 154, pp. 118–124, 2018.

[3] J. Ma, Y. Yang, H. Wang, L. Li, Z. Wang, and D. Li, "How much CO_2 is stored and verified through CCS/CCUS in China?," *Energy Procedia*, vol. 154, pp. 60–65, 2018.

[4] M. Dejam and H. Hassanzadeh, "Diffusive leakage of brine from aquifers during CO_2 geological storage," *Adv. Water Resour.*, vol. 111, no. June 2017, pp. 36–57, 2018.

[5] S. S. Tupsakhare and M. J. Castaldi, "Efficiency enhancements in methane recovery from natural gas hydrates using injection of CO_2/N_2 gas mixture simulating in-situ combustion," *Appl. Energy*, vol. 236, no. November 2018, pp. 825–836, 2019.

[6] Y. F. Sun *et al.*, "Gas hydrate exploitation using CO_2 /H_2 mixture gas by semi-continuous injection-production mode," *Appl. Energy*, vol. 240, no. January, pp. 215–225, 2019.

[7] M. Godec, V. Kuuskraa, T. Van Leeuwen, L. Stephen Melzer, and N. Wildgust, "CO_2 storage in depleted oil fields: The worldwide potential for carbon dioxide enhanced oil recovery," *Energy Procedia*, vol. 4, pp. 2162–2169, 2011.

[8] N. I. Furuvik and B. M. Halvorsen, "Simulation of CO_2 injection in fractured oil reservoir," pp. 347–355, 2015.

[9] Y. Wang, J. Hou, and Y. Tang, "In-situ CO_2 generation huff-n-puff for enhanced oil recovery: Laboratory experiments and numerical simulations," *J. Pet. Sci. Eng.*, vol. 145, pp. 183–193, 2016.

[10] a T. F. S. Gaspar, S. B. Suslick, D. F. Ferreira, G. a C. Lima, and S. U. Campinas, "SPE 94922 Economic Evaluation of Oil Production Project with EOR : CO_2 Sequestration in Depleted Oil Field," 2005.

[11] F. Van Bergen, "GLOBAL CARBON DIOXIDE STORAGE POTENTIAL AND Ecofys

TNO-NITG EEP-02001 by order of the : Rijksinstituut voor Volksgezondheid en Milieu," 2004.

[12] G. Heddle, H. J. Herzog, and M. Klett, "The Economics of CO_2 Storage," 2003.

[13] D. N. Nguyen and W. G. Allinson, "SPE 77810 The Economics of CO_2 Capture and Geological Storage," *One Petro*, no. x, pp. 8–10, 2002.

[14] Energy Information Administration (EIA), "Oil and Gas Lease Equipment and Operating Costs 1986 Through 2001." [Online]. Available: https://www.eia.gov/oil_gas/natural_gas/data_publications/cost_indices/c_i.html. [Accessed: 28-May-2019].

[15] X. Wang, K. van 't Veld, P. Marcy, S. Huzurbazar, and V. Alvarado, "Economic co-optimization of oil recovery and CO 2 sequestration," *Appl. Energy*, vol. 222, no. April, pp. 132–147, 2018.

[16] K. Van't Veld, C. F. Mason, and A. Leach, "The economics of CO_2 sequestration through enhanced oil recovery," *Energy Procedia*, vol. 37, pp. 6909–6919, 2013.

Chapter 5

Conclusions and Recommendations

5.1. Conclusion

The reservoirs of depleted oil fields in Pakistan offers huge underground geological storage of CO_2 and it also has a significant effect on the parameters of depleted oil field. However, the magnitude of difference in improved recovery depends on the earlier stages of the depleted oil field. There are many hurdles to making CCS a reality, but none appear impossible. our goal should be to support R&D, as well as pilot CCS projects so that widespread deployment of CCS can begin. This is an aggressive goal, but the climate problem compels us to act with fierce urgency.

5.2. Recommendations

Recommendations to be pursued for better understanding of carbon sequestration operation can be:

- There are many fields in Pakistan which are declining at their production rate and are favourable for CO_2-EOR operation but an adaptation of this technology and its success mainly dependent on the economics of the project and availability of CO_2 sources.
- CO_2 integrated with other WAG technology is another option which can yield greater outcomes, this technology has already been recommended by many industry professionals and researchers for oil fields situated in Sindh, solely use of CO_2 throughout its project life can have lower recovery.
- Sensitivity Analysis to carried out to check the effect of change in oil prices, discount rate, and other varying economic parameters involved in CO_2-EOR operations for getting more accurate economic approach for the operation.
- The operator companies of these declining oil field in Pakistan should establish research centers involving faculty members from qualified research universities for screening and

identification of various fields in Pakistan which are feasible for CO_2-EOR studies. Reliable simulation work needed so that more efficient results can be concluded through such work.

- A comparison between Schlumberger ECLIPSE reservoir simulator and other simulators can be carried out to find out more accuracy of results.

Simulation Study of Fractured Reservoir for Enhanced Oil Recovery

Anaiz Gul Fareed[a], Muhammad Zubair[b]1

[a]Centre for Advanced Studies in Energy National University of Sciences & Technology, 44000 Islamabad, Pakistan
[b]Centre for Advanced Studies in Energy, National University of Sciences & Technology 44000 Islamabad, Pakistan

Abstract

Pakistan economy is growing steadily, and this growth ultimately demands higher energy consumption which adds the utmost pressure on countries economy. Pakistan basically relies on its primary energy sources of oil and gas and these indigenous resources are insufficient to have an impact in resolving the current energy crisis of this growing economy, as a result Pakistan has to import large amount of petroleum and petroleum based products from other countries, which ultimately increases further increasingly trade expenses on national economy. Pakistan production to date has been characterized by extensively large oil and gas reservoirs which are undergoing natural depletion with the passage of time. This research is an attempt to extrapolate the potential lies in Pakistani reservoirs after undergoing natural depletion using Enhanced Oil Recovery (EOR) methods. This research discussed reservoir simulation study of XYZ oil field which was discovered by E&P company in Pakistan in Potwar basin in 1989, it is fractured carbonate reservoir and comprises of two different formations of Chorgali & Sakesar. after production of six years with the cumulative production of about 6 million barrels of oil, reservoir pressure rapidly declined and oil production declines from 4000 to 1800 bbl/day. Water flooding was started in earlier part of 1990`s to arrest the oil production decline by pressure maintenance, with the injection of water production of oil was restored back but after injection of two years, water breakthrough occurred and that has resulted in rapid decline in production to level of 550 bbl/day. water flooding is still being carried out in this field and production is declined to much low as 175 bbl/day with cumulative production of oil as of October 2016 is 13.83 MMbbl out of total 37MMSTb of OOIP. This study resulted by reservoir simulation that both chorgali and sakesar reservoirs have potential to drain the remaining recoverable reserves by conventional Enhanced oil recovery utilizing gas injection.

Keywords: *Oil Production; minimum miscible Pressure, Efficient oil recovery; Reservoir simulation; residual oil; Water flooding; EOR Theoritical potential; Gas Injection;*

1. Introduction

Pakistan oil and gas resources are scattered throughout the region with lots of oil potential to be recovered from naturally depleted reservoirs. Crude oil production in Pakistan reaching an all-time high of 98 Mbbl/day in November 2014, and averaged 64.35 Mbbl/day from 1994 to 2016 [1]. By looking current indigenous oil and gas resources of Pakistan, Enhanced oil and gas recovery is going to be the future option for Pakistani supplies sooner or later, when conventional natural gas deposits will not run short and oil reservoirs will not have the capacity to produce under their present natural exhaustion systems[2].

The structure of XYZ field is located in the eastern part of the Potwar Basin. The fractured carbonate reservoir of comprises of two producing formations; Chorgali and Sakesar. The said structure was first explored in 1980. The company drilled Well-01 and hydrocarbons were observed in the Chorgali as well as in the Sakesar formation. The well was tested and an oil production rate of 20 bbls/day was recorded. After a few months of observation, the

*Aniaz Gul Fareed. Tel: +92-300-3093815
E-mail address: anaiz.pk22@gmail.com

Company declared this well as non-commercial and Field was taken over by other E&P company.
The field came on regular production in October 1989 at the oil rate of 4000 bbl/day and the initial reservoir pressure of Sakesar was recorded as 5709 psia. The bubble point pressure of the hydrocarbon fluid was measured at 2948 psia. Pressure survey conducted on 28th August 1995 showed that reservoir pressure had gone below the bubble point pressure and had declined from 5709 psia to 2477 psia. Consequently, to arrest the decline in reservoir pressure and production, water injection was started in Sakesar formation.
To-date, 4 wells have been drilled on this structure. Two of these wells are producers while third well is water injector. Another well was abandoned due to mechanical problems. The cumulative production as of October 2016, is about 13.83 MMSTB oil from the field. An Integrated Reservoir Simulation Study was conducted to address the reservoir management problem of the field such as remaining recoverable reserves and requirement of the new wells for optimum recovery of the oil from the field.

2. Reservoir Geology

The reservoir of XYZ field is steeply dipping asymmetrical anticline structure with major faults on its southern limb. The two main reservoirs in the geological structure are Chorgali and Sakesar while some other formations like Murre shales also provides the top portion to its seal. The Chorgali formation predominantly composed of Shale which is hard medium hard in nature and Dolomite and which is mainly dense. The major composition in Sakesar is of Limestone which comes in contact with all three wells in fractured region. Upper part is fractured in injector well while lower part is fractured in producer. The production from the formation is from the fractured area in both wells.[3]

3. Reserve Estimates

As it is a fractured carbonate reservoir which has very low matrix porosity so using volumetric method was not considered as reliable method for reserve estimation. Material balance was used to determine the oil in place. Material balance determined oil in place of 35.55 MMSTB from both formations. There was no aquifer support and material balance also confirm that depletion drive mechanism for the reservoir with no oil water contact was seen in this reservoir during drilling. Formation compressibility is the major parameter for determination of oil in place in this type of reservoir. Number of sensitivity analysis were carried out in the material balance to illustrate the effect of the formation compressibility on the oil volume.

4. Fractured Formation

Two types of fractures were observed from these three wells drilled on the structure on this field. The oil production is only through these fractures while matrix porosity is too tight to contribute in the flow system. The initial reservoir pressure of Sakesar was determined. The pressure survey conducted showed that reservoir pressure had declined from 5709 psia to 2477 psia which is lower than the bubble point pressure of 2948 psia. As a result of this depletion below bubble point pressure, production declined from 3800 to 2000 bbl/day. Consequently, to arrest the decline in reservoir pressure and production, another well was drilled for water injection and was completed in upper part of Sakesar formation.

5. Waterflooding

The application of waterflooding has been increasing throughout the oil industry, it is the most common secondary assisted recovery method applied by oil industry when oil production rapidly declines and not able to produce with their current depletion level, water flooding mostly carried out for increased in oil recovery by an improvement in sweep or displacement efficiency. In addition to the enhanced oil recovery objective, water flooding may also be used in order to maintain the reservoir pressure when the aquifer or gas cap is insufficient for this purpose.
Water injection was started in March 1998 with the maximum rate of 8500 bbl/day. Within two month of water injection, increase in oil production and pressure were observed. The water injection was continued with this rate and the oil production of 3800 bbl/day from the Well-01 was restored. On the other hand, no effect of increase in the oil production was seen in the Well-02, which was completed in Chorgali formation. After the achievement of maximum oil production of 3800 bbl/d, sudden decrease in the oil production started. Rapid decrease in the oil production from 3800 to 350 bbl/day was due to early water breakthrough in the Well-01 which was not envisaged by the early studies.

At present, the oil production from both wells have stabilized at the rate of 255 and 110 bbl/day respectively with the water injection rate of 2000 bbl/d. The water production from both wells Well-1 and Well-2 are 85.6% and 37 %, respectively.

It was observed in the study that upswept oil is still present in the Chorgali and Sakesar formation, which can be met by CO_2-EOR operations in field. CO_2-EOR is an appealing technique due to its potential to increase oil production from developed oil fields and in the meantime decreasing carbon footprints from atmosphere. CO_2 is more favourable fluid and make it good choice for injection as compare to other injection fluids because it is miscible with crude oil and also it is less expensive than other similarly miscible fluids. [4]

6. CO_2 Injection in Fractured Reservoir

This study concentrates on CO_2 injection in carbonate reservoirs including simulations of CO_2 dispersion in the porous and permeable rocks. Carbonate reservoirs are characterized by having very low permeability and very high heterogeneity causing significant amount of CO_2 to be recycled. The oil production from carbonate reservoir is nearly half the production from sandstone. While the CO_2 used is around 60% or less. [5]

Carbon Dioxide has the highest recovery factor as compared to the other injection gases, there are certainly some issues in availability and handling of carbon dioxide injection and equipment's, therefore it is very wide to find out minimum possible injection with maximum benefits. Maximum recovery and NPV can be achieved with minimum injection.[6]

7. Reservoir Simulation

Basic reservoir engineering simulation is the descriptive simulated model of the reservoir to describe fluid flow performance. The accuracy of model performance prediction depends on how closely the virtual model simulates the actual geophysical, geological, rock and fluid properties of the reservoir. On this basis of available information of proposed XYZ field, a model was setup to simulate reservoir behaviour. Great care should be taken to improve the description of reservoir using integrated approach[3].

8. Pressure History

Pressure history of well-1 tested Formation is Sakessar for Oil Field XYZ, RTKB is 541.7 m where as its Bubble Point Pressure is 2934 Psi, Datum depth is 2475 m and Reservoir Temperature falls at 222°F

Table 11 Sakessar Pressure History of Well-01

Date	Cumulative Oil Produced (MSTB)	Cumulative Gas Produced (BSCF)	Gauge Depth (M)	Res; Pressure (Psia)	Pavg @ Datum (Psia)
22.08.89	34.599	-	2860	5523.7	5670.5
29.11.89	108.063	0.07999	3005	5575	5589
09.03.90	237.506	0.19671	3005	5336+	-
29.03.90	432.67	0.33498	3005	5292	5283.5
22.10.90	1076.19	1.00345	3007	4798	4788.6
23.03.91	1499.088	1.37095	3005	4500	4487
06.06.92	3038.83673	2.829565	3005	3465	3455++
16.12.92	3686.49137	3.5423	3005	3035	3026
24.11.93	4635.52	4.391445	3005	2698	2709
28.08.95	6077.457	5.924	3005	2384	2477

14.08.96	802.356	7.985	3005	3200	3313

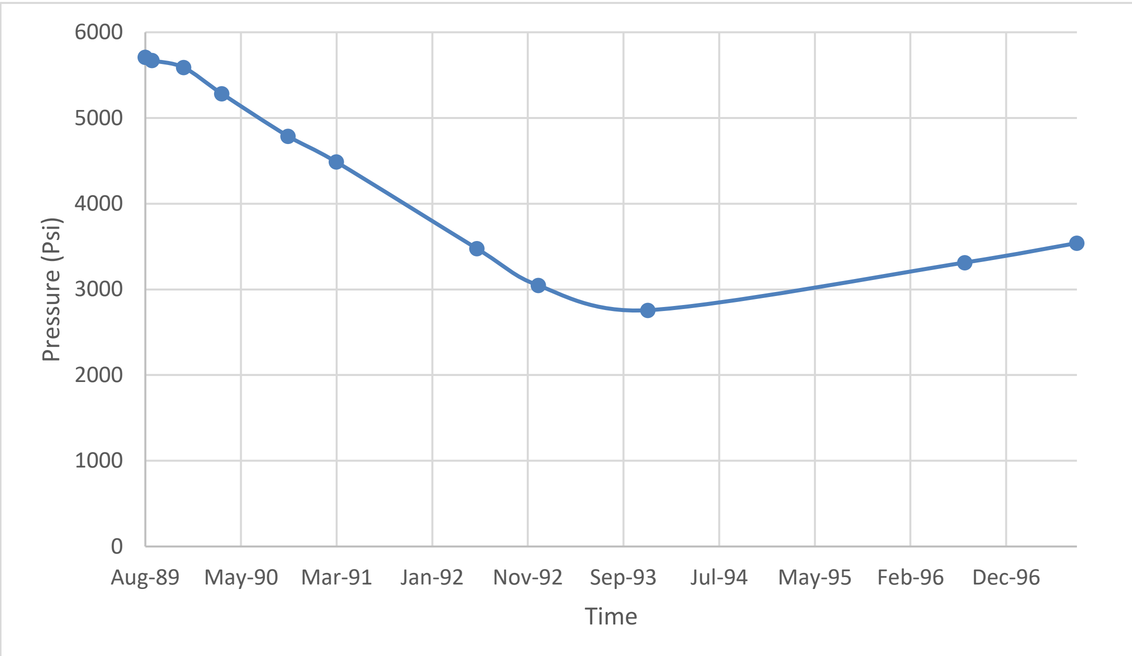

Figure 27 Sakesar Reservoir Pressure Vs Time

For Well-02 the tested formation is Chorgali, its RTKB is 537.2 m, Bubble Point Pressure = 3265 Psi Datum depth is 2380 m and Reservoir Temperature is around 212°F

Table 12 Chorgli Formation Pressure History for Well-02

Date	**Cumulative Oil Produced (MSTB)**	**Gauge Depth (M)**	**Res: Pressure (Psia)**	**Pavg @ Datum (Psia)**
23.9.90	0	874.5	5271+	5393
15.10.90	12.331	2825.7	4905	5070.2
26.03.91	238.475	2875	2730	851.6

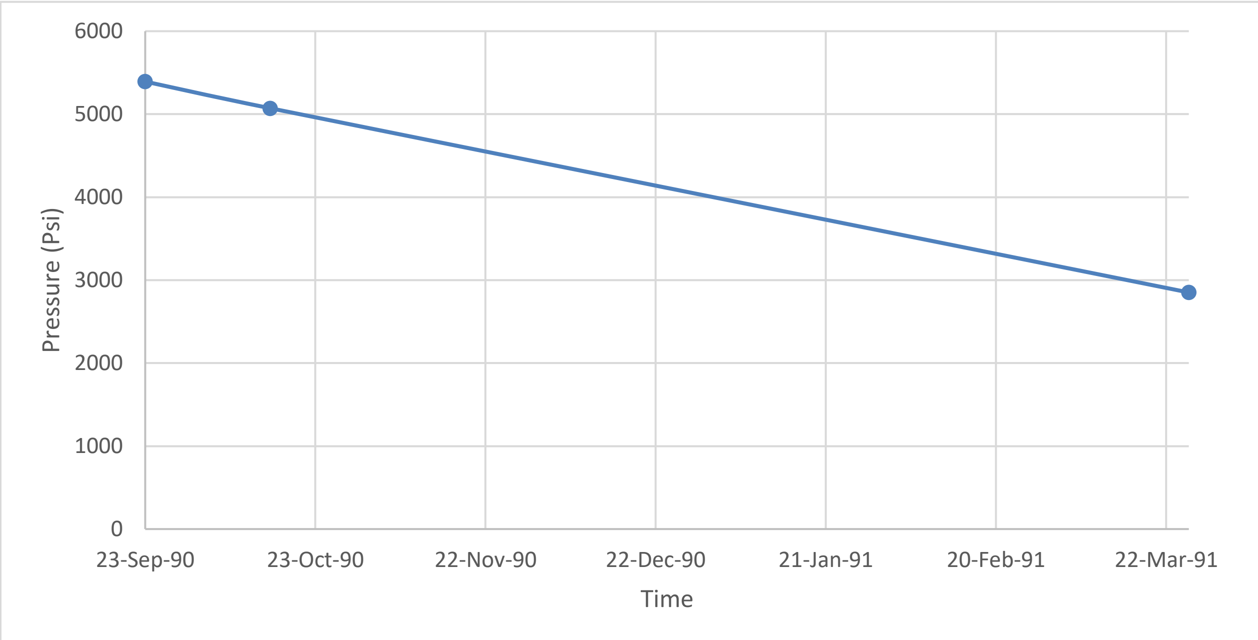

Figure 28 Chorgali Reservoir Pressure Vs Time

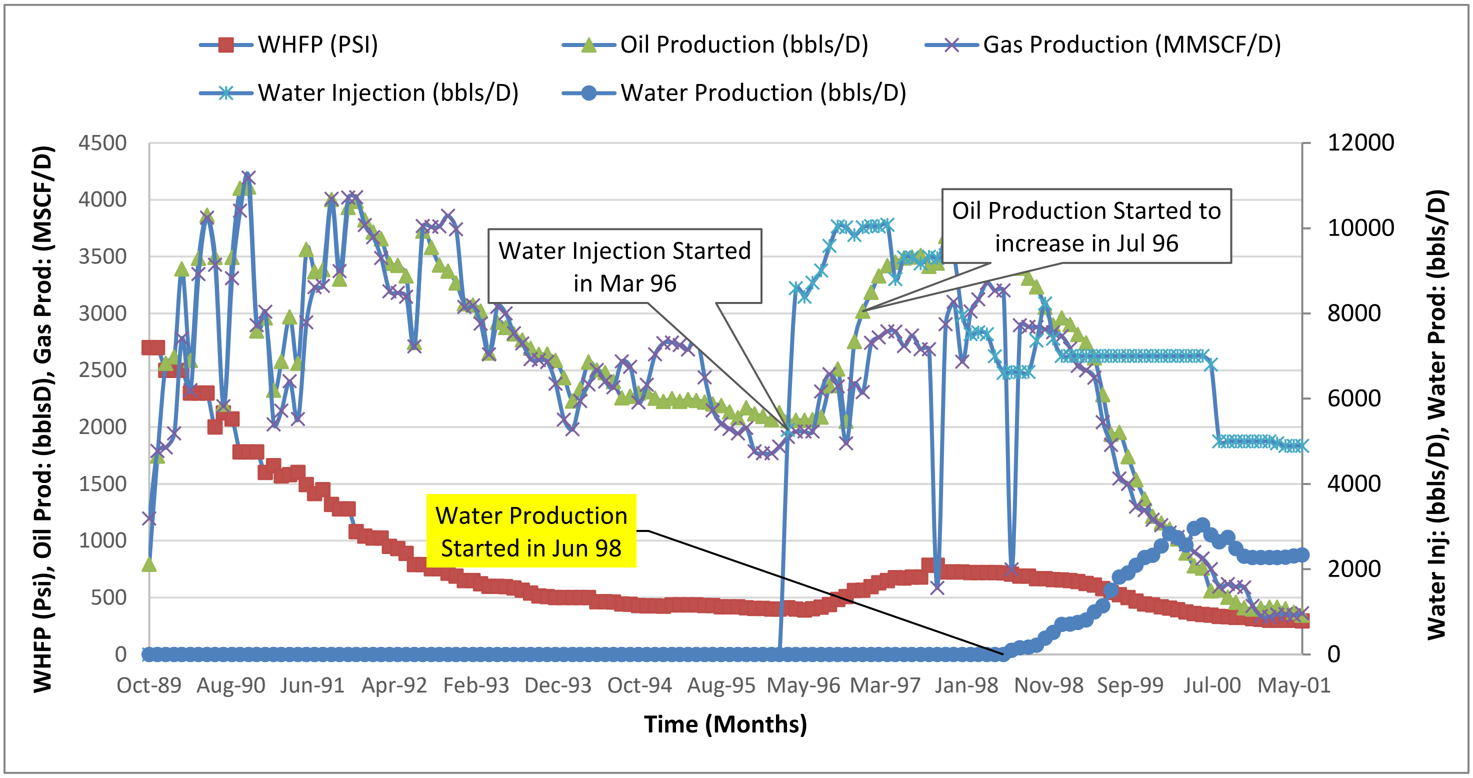

Figure 29 Production Profile (Sakesar)

9. PVT Analysis

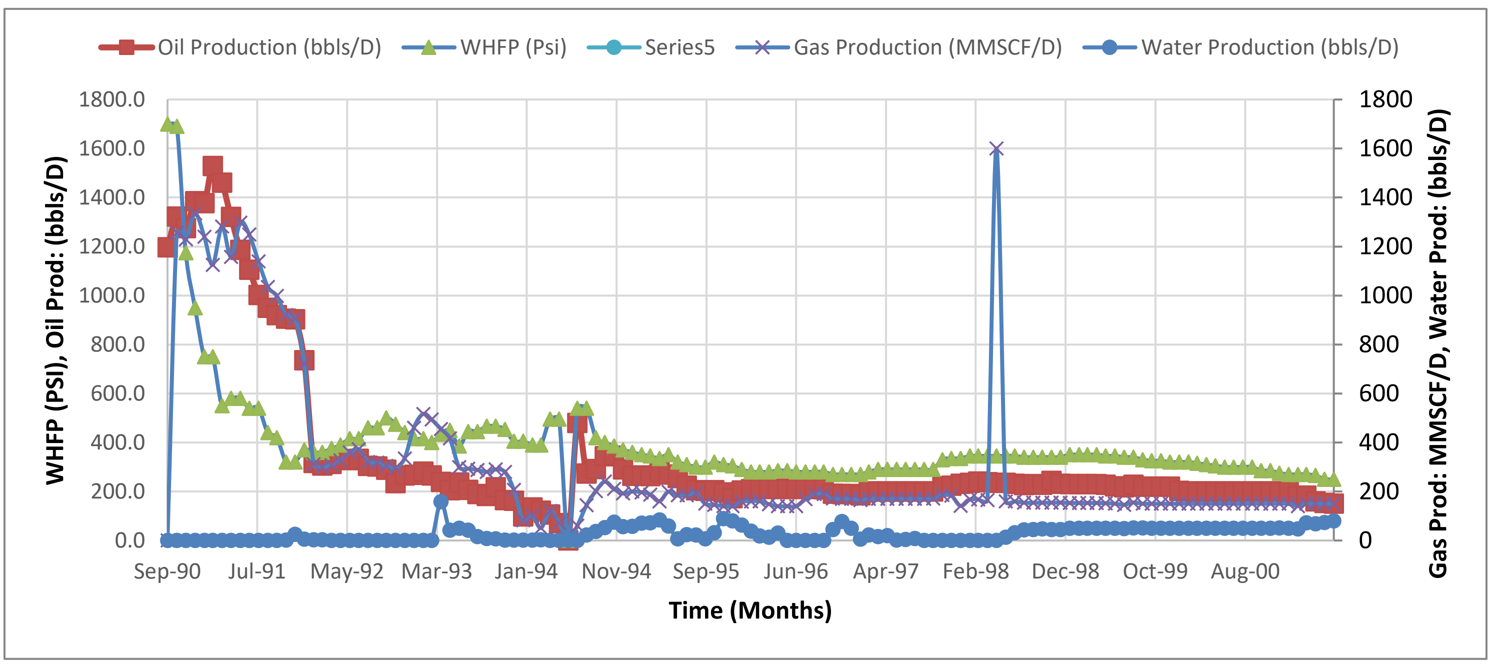

Figure 4 Production Profile (Chorgali)

Table 13 PVT Analysis

Pressure (PSIG)	GOR SCF/STB	Bo Res bbl/STB
5000	989	1.568
4500	989	1.579
4000	989	1.592
3500	989	1.608
2934	989	1.626
2600	896	1.546
2200	782	1.469
1800	667	1.409
1400	554	1.3349
1000	477	1.292
600	329	1.23
283	167	1.162

10. Conclusion

EOR has the significant effect on enhancing domestic crude oil production from Fractures Carbonate reservoirs. The impact is related too when injecting fluid gets the accelaerated entry into the matrix block, subsequent effect on gravity capillary drainage and capillary induced displacement. Ultimate oil recovery increases by CO_2 injection with increasing reservoir pressure in a single matrix fracture system. Oil recovery rate affected by CO_2 injection rate because of the importance of oil-vaporisation and diffusion mass transport.

Acknowledgments

The authors would like to thank the Reservoir Department and the Production Department of Oil & Gas Development Company Ltd (OGDCL) for providing support to carry out this study along with valuable contributions.

Nomenclature

MMSTB	= Million Stock Tank Barrel
EOR	= Enhanced Oil Recovery
CO_2	= Carbon dioxide
NPV	= Net Present Value
RTKB	= Rotary Table Kelly Bushing
Res:	= Reservoir

References

[1] "Pakistan Crude Oil Production | 1994-2017 | Data | Chart | Calendar." [Online]. Available: http://www.tradingeconomics.com/pakistan/crude-oil-production. [Accessed: 17-Jan-2017].

[2] B. Amjad, D. Munawar, and M. U. Javeed, "EOR Prospects for a Mature Oil Reservoir in an Oil Field of Potwar Region, Pakistan," in *Carbon Management Technology Conference*, 2012.

[3] M. S. K. Jadoon, A. Hameed, and M. M. Akram, "An Integrated Reservoir Simulation Study of Fimkasser Oil Field," vol. 13, no. June, pp. 37–58, 2003.

[4] C. C. and A. C. F. C. D. Melzer, L. Stephen, "Carbon Dioxide Enhanced Oil Recovery," no. February, p. 18, 2012.

[5] N. I. Furuvik and B. M. Halvorsen, "Simulation of CO_2 injection in fractured oil reservoir," pp. 347–355, 2015.

[6] S. Ahmed, A. M. Khakwani, I. Ahmed, and O. H. Khan, "Enhancing Recoveries from a Low Permeable Gas-Condensate Reservoir through Hydraulic-Fracturing and EOR Technologies," *PAPG/SPE Pakistan Sect. Annu. Tech. Conf. Exhib.*, 2016.

Economic Evaluation & Feasibility Study for Enhanced Oil Recovery Research

Anaiz Gul Fareed[a], Muhammad Zubair[b]2

[a]*Centre for Advanced Studies in Energy National University of Sciences & Technology, 44000 Islamabad, Pakistan*
[b]*Centre for Advanced Studies in Energy, National University of Sciences & Technology 44000 Islamabad, Pakistan*

Abstract

Pakistan dependence on fossils fuels primarily characterized by large oil & gas reservoirs undergoing natural depletion with the help of strong natural aquifer drives, due to this Pakistan is facing severe energy crisis. In spite of the fact, nature has blessed this country with enormous energy potential. The shortfall of energy supply is increasing while demand continues to rise high but still, there has been no systematic and methodical attempt to define Enhanced Oil Recovery (EOR) in the country.
This research presents an economic feasibility study for EOR projects. EOR projects shatter down in many favourable places due to its economic value, projects favoring EOR need to prove themselves more economical than previously due to wide varied oil prices around the world. This present study considers improvement in EOR feasibility, challenges faced by EOR projects, and sketches a summary on how through EOR residual oil left in place and produced at the surface after primary and secondary recovery, which then can be used to increase domestic oil production and contribute in the global energy mix. The economic analysis of currently uneconomical EOR processes can be utilized to determine the most effective direction for research. It determines whether fundamental technical limitation block advancement of the practical process and the highlights of a procedure to which the process financial aspects are generally most sensitive. By characterizing the most significant questions we can focus the research effort and maximize the accomplishment. Each potential EOR project must be assessed for its particular condition. The rate of return and cost values can`t be specifically applied to other EOR conditions. Yet can be utilized as a manual for relative profitability

Keywords: *Oil Resource Base; EOR cost Effectiveness; Maximize profitability; EOR operations cost; Economically recoverable resources;*

1. Introduction

Pakistan's oil and gas fields are some of the oldest in the world. Pakistan production of crude oil was 84,000 barrels per day and 3.8 Billion cubic feet of gas per day[1]. It is a net importer of crude oil and petroleum products, with a serious balance of trade imbalance. Crude oil imports were rose to $ 13 Billion in 2017-18[2].
Any increases in indigenous oil and gas production will help the nation in 3 ways:

- by reducing fuel supply shortages
- by helping to relieve the electricity shortage
- and by reducing imports.

Already Pakistan is having to shed loads during peak fuel and electricity demand periods. Consequently, the value of increased domestic production must be calculated by its value in reducing productivity problems that impair GDP, not by market values of oil products alone.
Most of Pakistan's oil fields are in decline. Many E&P companies have gone through the first several stages of

*Aniaz Gul Fareed. Tel: +92-300-3093815
E-mail address: anaiz.pk22@gmail.com

production:

- At first, wells produce by their own pressure.
- Next, the oil must be pumped from underground.
- Third, water is injected into wells to float the oil toward gathering points.

These standard methods recover 30-40% of the oil in a typical field. There are other techniques, collectively known as Enhanced Oil Recovery (EOR) which can raise recovery to over 60%. Payback can be very high in specific fields, but effectiveness depends on high tech studies of the underground geology and geophysics. In the past, many E&P companies have been doing studies and screening of fields for EOR but are reluctant to spend money in absence of adequate international expertise.

One of the likely technologies to be used in EOR in Pakistan is CO_2 injection. There are supplies of CO_2 available from gas wells with high CO_2 content and from Clean Coal carbon capture technologies under consideration. Approximately half of the potential CO_2 demand for CO_2-EOR operations in already discovered can be met by large, identified anthropogenic CO_2 sources within small comparable distance to existing CO_2 pipeline serving projects[3].

2. Secondary Oil Recovery in Potwar Region

XYZ field was initially discovered by one E&P company of Pakistan in 1980 but declared non-commercial due to low productivity of (20 BOPD). Then after several years there made a made a commercial discovery through a side-tracked hole in 1989. It is a naturally fractured carbonate reservoir with insignificant matrix porosity and permeability. The production is mainly through the fractures. The field has been on production since 1989. A waterflooding was started in 1996 and is still ongoing on at a reduced water injection rate. A total of four wells have been drilled in the field. two producer wells, one water injection well and another well is plugged and abandoned. Approximately 13.8 million barrels of oil have been produced from the field. (OOIP) was about 34 million barrels. Water breakthrough had occurred in 1998 and currently, 175 barrels of oil per day are being produced. However, there is the possibility of increasing oil production and recovering additional oil reserves through the implementation of a suitable EOR scheme.

3. Technology Advancement

CO_2-EOR has an enormous potential of increasing domestic oil production, it also stores a significant volume of carbon dioxide which is also very helpful to combat greenhouse gases emissions in the natural environment.

Many foreign service company expert's technologies and plant equipment machinery stand a good chance to enter the Pakistan market at an early stage and establish themselves as market leaders. If successful, this would open great opportunities for many companies in Pakistan. An expert consultancy firm may be engaged to perform a detailed study to evaluate the proposed field and recommend the appropriate EOR model. The expected cost of the feasibility study is $600,000-900,000, which includes modeling, data processing, and testing. Usually, Feasibility study expected to take about 6 to 9 months, but in some cases, it may take more than a year.

Expected technology and Plant equipment and machinery for investment and for the initial application of EOR after the study would be between $3 and $5 Million.

It is expected that the production, which is in decline, can be reversed and increased to higher levels as determined. if EOR will be used later, the initial drilling patterns may be changes to later increase overall EOR recovery.

4. Project Description

The EOR Project will consist of these stages

- Selection of an expert consultant, "Consultant".
- Feasibility Study to verify and assess the potential of the field for EOR.
- EOR equipment design, procurement, and installation.
- EOR operation

The Feasibility Study will take 9-12 months to complete

Consultant Shall:

Meet E&P company client to establish working and reporting relationships, determine levels of knowledge of counterparts, review existing data, assess available tools and analysis facilities, determine availability of EOR media such as CO_2, N2 or polymer flooding from other wells or CO_2 recovery programs, determine the need for supplemental data collection, and verify the standards and criteria by which client will accept the Feasibility Study. It is worth to mention that CO_2 gas field is located more than 600 km flight distance from the proposed oil field. A pipeline of more than 600 km will be required to transport CO_2 for injection for EOR purpose. It is important for the consultant to evaluate another EOR process in addition to CO_2.

4.1. Data Collection/Inputs

Review existing data and studies

- Team includes professionals from major disciplines of oil industry likes Reservoir Engineering, Geology and Geophysics.
- Data will be reviewed and report will be made on data quality assessment.
- The outcome data product will be shared with consultant and other technological personnel for further refinement, recommendation for field project development [4].

4.2. Seismic & Geological Analysis

Conduct seismic and geological analysis to determine the 3-dimensional structure of the field

- Interpretation work to be carried out using two-dimensional (2D) data, in which all the time, depth, and contour maps are generated on software.
- This Geological model made from geoframe software helps in the precise interpretation and geological setting and selection of the area.

4.3. Petrophysical Analysis

Conduct petrophysical analysis for reservoir characterization and input for the model and to determine the best methods to free and lift oil from the reservoir.
The different analysis of production and quantitative well log data determines petrophysical properties of reservoir. The main task for these petrophysical analysis is to conduct precise calculation and evaluation of major petrophysical properties like capillary pressure, relative permeability, porosity, hydrocarbon saturation, and irreducible water.

4.4. Reservoir Engineering and Determination of Initially Oil in Place

- Perform basic reservoir engineering and verify the calculation of oil initially in place using current technology
- PVT laboratory analysis reports of different fluid samples are reviewed, samples which are reviewed recovered from the field.
- Rock properties reports are reviewed for determination of relative permeability.
- Consultant will analyse all the data and will estimate the reservoir model based on obtained data and reservoir parameters.
- Completions diagrams and spreadsheets for all wells are reviewed and any change can be made if required for better flow efficiency
- Volumetric oil in place calculated for each geological layer. In case of multi layers it subdivided into model layers.

4.5. Reservoir Simulation Study

Select and initialize an appropriate EOR simulation model

Model Initialization:

- A 3D simulation model would need for better result and evaluation of results.

- At the present field is on water flooding and probably secondary aquifer have been generated in the reservoir. About 25 million barrels of water have been injected and 13.8MMbbls of oil have been recovered.
- Geological phase will be the first phase for model development and after that model study will propose reservoir grids in two dimension and number of cells to represent multi model layers in geological model.
- Simulation work must be performed lab fully equipped with latest EOR/Reservoir simulator.

5. Enhanced Oil Recovery

EOR feasibility study will be the base study to screen the resevoir data and decide either optimum tertiary recovery method is applicable or suitable to maximize oil recovery from the depleted oil field or not.
Number of simulations will be run on EOR optimum methods and examined by professionals for its practical feasibility and recovery of hydrocarbon in economic condition.

6. Changes in Drilling and Completion Specifics

Drilling and completion costs can comprise the significant share of capital investments for any CO_2-EOR project study, costs depend on number of wells to be drilled, other important factors include overburden, depth, well design and region[5]. the feasibility of drilling new wells. Recommend optimum flow rates, completion size, and number of wells, well location and artificial lift for all reservoirs.

6.1. Design the appropriate EOR Implementation Plan

- Select the most effective, environmentally safe and economically feasible Enhanced Oil Recovery strategy
- Determine the capital cost of EOR equipment, additional wells, gathering and supply pipelines and pumps or compressors, and EOR operating costs including labor and injection media
- Conduct economic analysis and evaluation of scenarios within the range of accuracy of the model
- Compatibility of EOR material with the reservoir

7. Economic Analysis & Evaluation

The size and value of the cost evaluation for captured CO_2 emissions offered by EOR consist of three major factors.

- The size and nature of indigenous crude oil resource base
- The ability of EOR to recover a portion of the stranded domestic oil
- The impact of alternative oil prices and cost of injecting a fluid that could be economically produced [6].

The majority of current and previous EOR projects are very large in scope, so they have been conducted in stages with major workovers with also infill drilling in some cases[7]

- Economic analysis is necessary while carrying out any big development project, and in each prediction case NPV, IRR, ROR and other indicators are analysed for economic profitability.
- Consultant will provide all the figures to client on capital investment and annual revenues by looking all the engineering solutions.
- Consultant will provide the recommended implementation plan for maximize economic oil recovery to the client and changes required in surface facilities and reservoir management for the life of the field.

Judging from results of the feasibility study of the proposed field, the client will need to conduct a superficial review of data for other fields that are candidates for EOR and project the potential for EOR at each site This review will help E&P client plan future production levels, staffing, and budgets around extended EOR applications.
Professionals like Geoscientist and Reservoir Engineers will perform fully inspection of feasibility study report and will evaluate the 3D model study and its practical application.
After careful evaluation and inspection, professionals will make report on feasibility study and will mention all the indicators necessary for economics analysis in their report of study.

8. Potential Obstacles

EOR may not be successful in Pakistan for a variety of technical considerations which the Feasibility Study will investigate and attempt to resolve. Applying EOR may prove too expensive, or increase yields too slowly to be financially feasible. If the Feasibility Study shows sufficient returns and reasonable probability of success, though, the client should enjoy unstinting support from all concerned GoP agencies. The project has benefits across the board for the industrial, commercial, and agricultural economies.

9. Implementation Financing

The proposed XYZ project must be able to pay for itself from increased oil production. The expected increase of oil production through implementation of EOR will generate additional reserves, also yield additional oil recovery. With 7-9 Million barrels still to be recovered, potential revenue at $ 40/BBL is expected to be above $ 250 Million. Whereas the current price of crude oil stands as $74/BBL[8]. Capital for the project will be provided by the client on a self-financing basis.

10. Risks Pertaining to Implementation of EOR Projects

Table 14 Risk and Possible Mitigation Strategy

Category	Risk Description	Possible Mitigation Strategy
Project	The FS may show EOR is not effective for proposed XYZ field in Pakistan.	Client and the consultant have sufficient judgment to terminate the FS if a review of existing geophysics data is not encouraging.
Operational	The FS may be positive but actual recoveries may not be sufficient to warrant investment at other fields.	The FS should provide a basis for judging the risk with several scenarios.
Commercial	Market prices may decrease to offset increased production by EOR.	Once demonstrated, the client can postpone EOR production as needed to wait out market downturns.
Political	No significant political risk foreseen	
Environmental	Increased fossil fuel emissions	Domestic production offsets imports, which actually have higher CO_2 emissions due to transportation costs.

11. Capital Cost Estimates

For each stage of the project including, capture, compression, transportation, and storage are divided into capital expenditures (CAPEX) and operating expenditures (OPEX). The OPEX mainly include the costs of labor, material maintenance and possibly monitoring costs[9].

The capital cost to prepare a field for CO_2 injection are very fuel dependent, other factors may also include

- Tubular condition,
- Wellbore integrity,
- Field location,
- Completion type,
- Reservoir depth
- and existing equipment utilization[7].

Cost of the XYZ field EOR project is expected to approach $10-12 million. This is not out of proportion to the cost of exploring, drilling, developing, and gathering oil from a new domestic oil field, so EOR cost is economically justified.   If successful, the EOR concept could be rolled out to the 15 fields now under consideration in Pakistan, as well as being applied to at least 10 new fields. Total rollout potential, then, for approximately 25 fields, would approach $200 million.

12. Development Impact

Infrastructure: Pakistan's economy is clearly being held back by oil and gas shortages, including lost production due to outages and load shedding, the poor financial condition of utilities, waste and imprudent use of gas and electricity, and balance of trade problems caused by rapidly growing imports of fossil fuels

Market Reform: Many of Pakistan's fuel supply problems are compounded by price subsidy policies, with irrational and counterproductive pricing differences in domestic and imported fuels. This project will result in EOR projects justified on probabilistic financial analysis, providing a strong and tangible input to fuel pricing policies. This may provide encouragement and support for efforts to reduce subsidies.

Human Capacity Building: Many of Pakistan's fuel supply problems are compounded by price subsidy policies, with irrational and counterproductive pricing differences in domestic and imported fuels. This project will result in EOR projects justified on probabilistic financial analysis, providing a strong and tangible input to fuel pricing policies. This may provide encouragement and support for efforts to reduce subsidies.

Technology Transfer: Pakistan has a large cadre of highly trained oil industry professionals who will benefit greatly from the demonstration of advanced technology for EOR.   In addition, the productivity of all sectors of the Pakistan economy is now impaired by frequent fuel and electricity interruptions. This project will lead to more reliable services, enabling all sectors to improve productivity.

13. Environmental Impact

Increased domestic production will offset imports, which actually have higher CO_2 emissions due to the higher energy costs for transportation and handling imported fuels. Increased fuels availability will also decrease pressure to develop domestic coal as a fuel supply with greater CO_2 emissions. However, Pakistan is planning to develop its coal resource on a high priority basis. Many studies are in progress to channel this development toward Clean Coal projects. Some of these will include carbon dioxide recovery features which will produce large quantities of CO_2, which will have to be sequestered by deep injection. Depending on the results of the Feasibility Study, CO_2 injection may be one of the preferred EOR methods.

14. Conclusion

Innovative research for implementation of EOR technology in Pakistan is mandatory, such that long time recovery of unrecoverable stranded oil in place from our resource base can be recovered. This research describes the sources for cost data by major components, such that future analysis can be planned to provide additional information for CO_2-EOR and CO_2 storage projects, it can also be used to investigate costs for site screening. Oil price in international market, price, and availability of CO_2 play a major role in project economics for CO_2-EOR projects. To reduce risks pertaining to CO_2-EOR projects in Pakistan, the government has to provide EOR tax incentives so that consequences can be managed and minimized. Advanced technology with proper design, implementation, surveillance and effective use of reservoir simulation is critical for a greater success of EOR projects in Pakistan.

Acknowledgments

The authors would like to thank the Reservoir Department, Production Department of Oil & Gas Development Company Ltd (OGDCL) for providing support to carry out this study along with valuable contributions.

Nomenclature

EOR = Enhanced Oil Recovery

GDP = Gross Domestic Product
E&P = Exploration and Production
BOPD = Barrels of Oil per day
OOIP = Originally Oil in Place
CO_2 = Carbon Dioxide
N_2 = Nitrogen
NPV = Net Present Value
ROR = Return on Risk
IRR = Internal Rate of Return
GoP = Government of Pakistan
FS = Feasibility Study
CAPEX = Capital Expenditures
OPEX = Operational Expenditures

References

[1] "Pakistan Crude Oil Production and Consumption by Year (Thousand Barrels per Day)." [Online]. Available: https://www.indexmundi.com/energy/?country=pk. [Accessed: 10-Oct-2018].

[2] "Country's oil import bill surges by 30.43pc to $12.928bn - Profit by Pakistan Today." [Online]. Available: https://profit.pakistantoday.com.pk/2018/06/20/countrys-oil-import-bill-surges-by-30-43pc-to-12-928bn/. [Accessed: 10-Oct-2018].

[3] M. Godec, V. Kuuskraa, T. Van Leeuwen, L. Stephen Melzer, and N. Wildgust, "CO_2 storage in depleted oil fields: The worldwide potential for carbon dioxide enhanced oil recovery," *Energy Procedia*, vol. 4, pp. 2162–2169, 2011.

[4] a. C. Brummert, J. R. Ammer, R. J. Watts, P. King, and D. a. Boone, "Economic Evaluation of a CO_2 EOR Flood at the Rock Creek Field, Roane County, West Virginia," *SPE Reserv. Eng.*, vol. 3, no. 3, pp. 829–834, 1988.

[5] C. Jablonowski and a Singh, "SPE 139669 A Survey of CO_2 -EOR and CO_2 Storage Project Costs," no. November, pp. 10–12, 2010.

[6] R. C. Ferguson, C. Nichols, T. Van Leeuwen, and V. A. Kuuskraa, "Storing CO_2 with enhanced oil recovery," *Energy Procedia*, vol. 1, no. 1, pp. 1989–1996, 2009.

[7] W. a. Flanders, R. a. McGinnis, and a. G. Shatto, "CO_2 EOR Economics for Small-to-Medium-Size Fields," *Production*, p. 14, 1993.

[8] "Crude Oil Price, Oil, Energy, Petroleum, Oil Price, WTI & Brent Oil, Oil Price Charts and Oil Price Forecast." [Online]. Available: http://www.oil-price.net/. [Accessed: 10-Oct-2018].

[9] a T. F. S. Gaspar, S. B. Suslick, D. F. Ferreira, G. a C. Lima, and S. U. Campinas, "SPE 94922 Economic Evaluation of Oil Production Project with EOR : CO_2 Sequestration in Depleted Oil Field," 2005.