Oil-recovery technique selection considering Exergy and Real Option analyses

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Executive summary

Global energy demand is on the rise while efforts are being undertaken to increase the share of renewables to the energy mix. Even though, it is expected fossil fuels will remain an important contributor to meet this demand in the following decades. This can be attributed to the existing infrastructure, fossil fuels abundance, their energy density and ease of distribution.

As of today, in the oil and gas industry, competing oil-recovery techniques are screened and evaluated with cashflow based methods such as the Net Present Value rule. This method is entirely based on economics and may neglect important aspects related to the techniques. If fossil fuels will still be produced, their contribution to climate change should be mitigated. This can be achieved by considering the efficiency of the techniques employed for extraction. Additionally, the oil and gas industry is subject to uncertainty as the oil price is volatile, as has been observed in the past few years. In order to evaluate competing techniques, it is advisable to also consider the impact of this uncertainty in their evaluation.

In this thesis, the applicability of two concepts for the screening of competing oil-recovery techniques is explored. The thermodynamic efficiency is assessed with the use of Exergy analysis and the uncertainty on the price of oil is considered through the use of Real Option theory.

Exergy analysis can determine the overall efficiency of a technique and its components through the analysis of the energy quality or theoretical amount of work a material stream could perform. If a material stream presents a certain amount of energy and this energy is dissipated without performing useful work, it is considered as Exergy destroyed. A relation can then be stablished between the Exergy invested as fuel, the Exergy destroyed and the Exergy obtained as product (from recovered oil) to define a technique´s efficiency. Additionally, if the technique´s associated costs are linked it is possible to stablish the cost per unit of Exergy recovered.

Real Options is based on the application of financial options assessment, like stock options, to options in applied settings, like oil-recovery techniques. It is based on the premise that firms have the flexibility to change from one strategy to other in response to the development of uncertainty. There are different approaches to solve real option valuations with the most commonly used being analytic and iterative approaches (Fernandes, et al., 2011). The real options to invest or postpone will be analyzed with these two different aproaches.

The analytic approach consideres the option of investing as a function of the value of an oil barrel, its standard deviation, the payout rate from each barrel and the risk free rate of return. From this relation, a differential equation is obtained and solved analytically.

The iterative approach relies on the definition of several oil-price random walks, in this thesis, one thousand. For each scenario a NPV is calculated and the mean of the distribution is considered as the option value. This approach captures the most likely scenarios but also the less probable.

In this research project, first, two oil-recovery techniques will be assessed with the conventional NPV rule, then with an Exergy analysis and finally, with a Real Option valuation to observe the differences and similarities between these approaches. The techniques analyzed in this thesis are: oil-recovery through water injection and oil-recovery through polymer injection. The main purpose of the water injection is to inject into the reservoir a low-cost fluid to push additional oil to the production wells. For the polymer injection, the added polymers viscosify the injected fluid and better swept is obtained recovering more oil. Even though, additional costs and energy requirements must be considered for the former technique.

The results obtained for the NPV, Exergy and Real Option analyses are presented in the table below. Each analysis was performed on a standalone fashion first, to analyze the information it provides. Then, for the comparative analyses, the water injection is considered as a base case and the additional economic, exergy and real-option performance for the polymer injection is used to make the comparison.

Analysis	**Parameter**	**Water Injection**	**Polymer Injection**	**Increment from base case**	**Better performing technique**
Standard NPV	NPV (millions)	$41	$69	$28	Polymer
Exergy	Exergy RF	94%	98%	4%	Polymer
	Exergy ROI	44	579	535	Polymer
	ExD/ExF	1.8	9.3	7.8	Water
	Ex P $/hour	160	252	92	Water
Real Options	Analytic RO (millions)	$65	$75	$10	Polymer
	Iterative RO (millions)	$51	$86	$35	Polymer

The recommended technique for the standard NPV rule is the polymer injection. It is important to mention that the technique becomes uneconomic after year 14 while the water injection presents positive cashflows up to year 20. If it is assumed that the technique will be stopped in the presence of negative cashflows then an early terminated polymer technique still shows a higher Net Present Value.

For the Exergy analysis, overall, it can be said that the polymer injection is more efficient. There is also a point were efficiency in the technique decreases under that of the waterflooding. This is a result on the reduction of Exergy product in comparison with the invested Exergy fuel and Exergy destroyed. For the ratio between Exergy destroyed and Exergy fuel (ExD/ExF), the waterflooding presents a better performance. Even though, this parameter does not take into account the Exergy recovered as product which is more favorable for the polymer injection. Finally, the exergoeconomic analysis reveals that the cost rate for a unit of Exergy product is 3.5 times as much for the polymer injection than for the waterflooding. This result also hints that the polymer injection requires bigger investment, even though, more oil is produced.

In the case of the Real Option analyzes it is observed that, for both the analytic and iterative approach, the preferred technique is again the polymer injection. For both approaches a higher option value is obtained in comparison with the NPV rule. This results from considering the presence of uncertainty on oil-price. For the analytic analysis it is important to mention that the optimal time of investment varies along the two oil-recovery techniques. For the water injection, the analytic approach recommends holding the investment decision in search of additional information on oil-price behavior. The option value increases with time but not enough to offset the time value of money, so the firm is better off investing right away. For the polymer injection technique, the analytic approach recommends exercising the option by year 12 but similarly, the increase in the option value does not offset the time value of money.

It was observed in the iterative Real Option analysis that the waterflooding presented less variance in its NPV distribution. This results from the notion that most of the oil recovered with this technique comes from the early years where uncertainty is less. For the polymer injection, additional oil is produced later where the price of oil is more uncertain.

As a conclusion, the following key-points are listed:

- For the standard NPV rule, exergy analysis and Real Options, the preferred technique is the polymer injection.
- Higher Capex and Opex for the polymer injection may turn the technique uneconomic earlier than the water injection technique.
- Overall, the polymer injection technique presents a better Exergy efficiency than the water injection. But for the later, this efficiency declines faster due to a higher Exergy fuel needed and higher exergy destroyed.
- For both techniques the Real Options show a higher option value than the standard NPV rule in consideration to the uncertainty.
- Such results cannot be generalized for all water injection and polymer injection applications but could serve as a basis to apply the discussed analyses to different oil-recovery techniques.
- The analyses considered in this thesis can be used as an individual assessment for obtaining economic and technical details about the technique, for improvements. Also, on a comparative level, to screen for more profitable but also more efficient alternatives.

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1. Introduction

It is estimated that global energy demand will increase by 30% in 2040 (International Energy Agency, 2017). With an ever-increasing energy demand, the use of greener forms of energy and fuels with lower carbon emission have gained increasing interest in public, private and regulatory circles. Figure 1 shows that while a decrease in fossil fuel use is expected in Europe, USA and Japan, in the rest of the world the demand for conventional sources of energy is expected to increase, especially in booming economies like China and India.

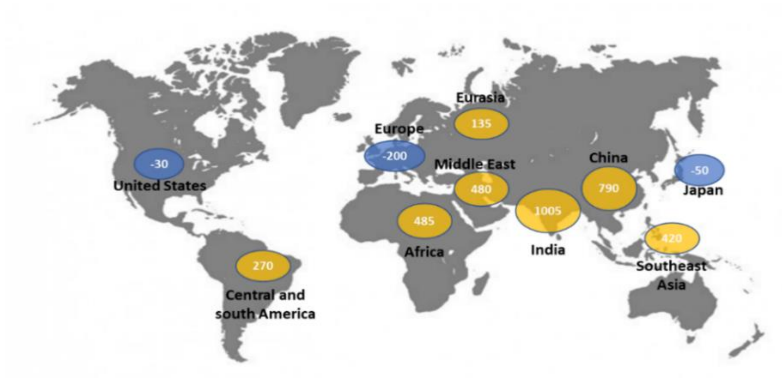

Figure 1. Change in energy demand 2015-2040 in thousand tons of oil equivalent (Modified from International Energy Agency, 2017).

As of today, fossil fuels are still used as the main source of energy for powering global economic activities. This is most likely due to the existing infrastructure, fossil fuels abundance, large energy density, and ease of distribution. According to estimates, the share of fossil fuels in the energy mix will remain present in the following decades. It is estimated that fossil fuels will have a share of 70% of the mix or more, if current trends prevail, up to 2040 (Exxon Mobil Corporation, 2017).

It can be observed in Figure 2 that solar and wind generated energy is expected to grow in importance. Even though, the global increase in energy-demand is likely to force fossil fuels to remain as an important source of energy for the coming decades.

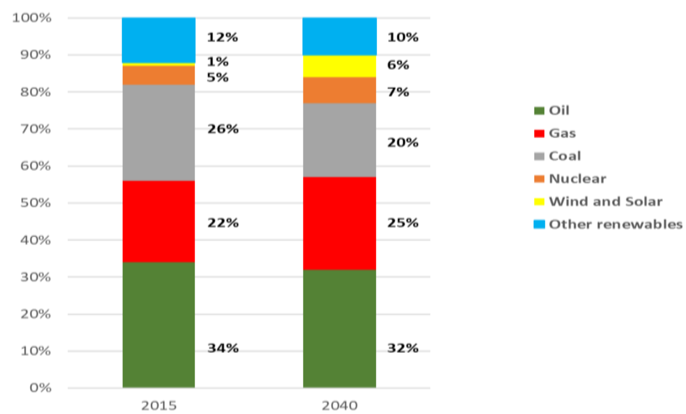

Figure 2. Percentage change in energy mix 2015-2040 (Modified from Exxon Mobil Corporation, 2017).

At the same time, fossil fuels are the main source of CO_2 emissions and for this reason their contribution on climate change should be mitigated during the transition to cleaner sources of energy.

After the oil primary production phase, usually only 10% of oil originally in place is recovered (Khan, 2007) which leave the option to undergo secondary oil-production projects. Figure 3 shows that the production performance of the most important giant oil fields in the world is steadely declining. These fields serve as a base line for stimating the production behaviour of smaller oil fields around the world since their combined production account for 40% of world production (Robelius, 2007). With oil fields maturing, the application of secondary oil-recovery projects is preferred over new field developments from a sustainability and efficiency point of view.

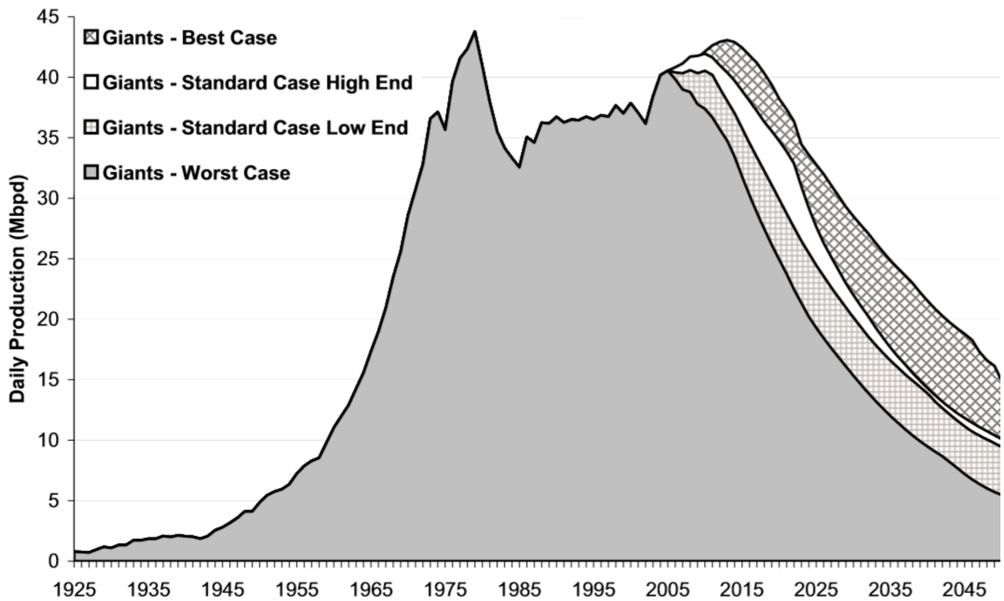

Figure 3. Estimated oil production from giant oil fields, in million barrels per day (Mbpd) (Modified from Robelius, 2007).

A feasible approach to meet the global energy demand and reduce the impact of the oil industry in the environment, is to produce fossil fuels using more-efficient recovery techniques. These production mechanisms should be evaluated using new measures besides the conventional project economics, where efficiency and uncertainties are not considered. In this thesis, the application of two concepts in the selection process of secondary-oil-recovery techniques will be evaluated, exergy and real option theory.

The term exergy is used as a measure of the quality of energy and represents the theoretical amount of work that can be performed with a certain measure of energy. Exergy is tied to a reference environment and considers that the material stream has the potential to perform work if it is out of equilibrium with this reference frame (Smith, et al., 2016). Exergy destruction can be considered as energy with the potential of performing useful work but that is instead wasted or dissipated into the environment. The exergy analysis of oil production systems has the potential to pinpoint the weakest links of the extraction process and therefore provides useful information for further energy use and green-house-gas emission optimization. Some authors have analyzed the application of exergy analysis in the oil industry (De Oliveira & Van Hombeeck, 1997; Finnveden & Ostlund, 1997; Nguyen, et al., 2013) focusing on the thermodynamic results. There is a gap in the literature on how to use the results from technical exergy analysis for project selection and evaluation.

On the other hand, real-option theory considers that a firm has the right but not the obligation to buy an asset or undertake a project in the future. It cannot reverse the investment should market conditions change adversely. This lost option value is an opportunity cost that must be included as part of the cost of the investment (Dixit & Pindyck, 1994). In secondary oil-extraction projects the effect of the shift in market conditions can affect the economic results of the projects due to uncertain parameters like the oil price. Figure 4 shows three different oil-price behavior scenarios proposed by the IEA which respond to the degree new policies on sustainable development are adopted. Even though these scenarios only consider possible implications on oil demand, they do exemplify the uncertainty effect present in the oil price behavior which in turn affect the profitability of projects.

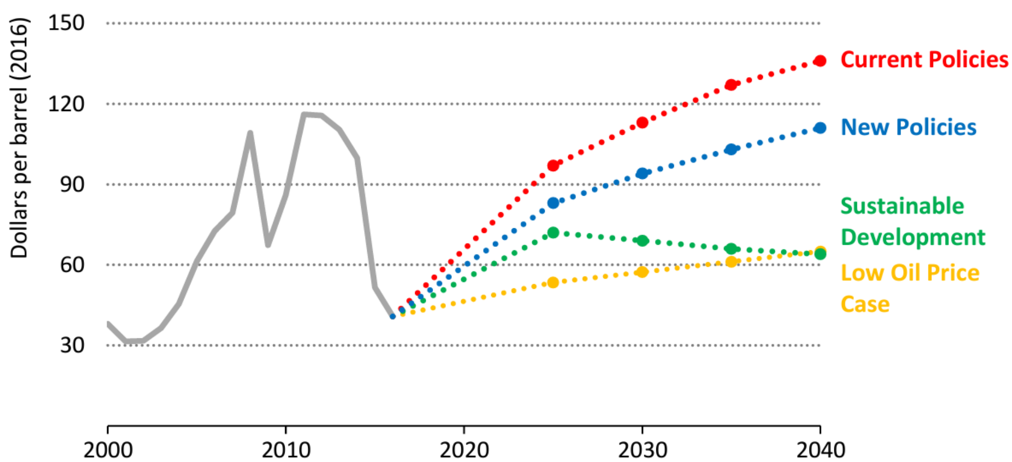

Figure 4. Average IEA crude oil import price by scenario (Modified from International Energy Agency, 2017-11-14).

By considering the efficiency of energy and the uncertainty effect, this thesis aims to explore the decision-making process expansion from only cash based decisions. As a case study, two different secondary-oil-recovery techniques will be evaluated from the exergy and real options point of view and the similarities/discrepancies will be analyzed. The oil-production techniques evaluated are waterflooding or water injection and polymer injection. The selection of these two techniques is based on their wide application, as it was the case decades ago (Herbeck et al., 1977) and even nowadays (Ramos & Akanji, 2017). In this thesis, first, the techniques will be analyzed first in a standalone fashion to obtain information for performance improvement. Then, for the comparative analysis the waterflooding is considered as a base case and the increments in NPV, exergy and real-options as a result of the application of polymer injection are used for comparison.

1.1. Research objective and questions

The objective of this research project, in order to fill the gap in relation to efficiencies and uncertainty in the evaluation of oil-recovery techniques, is:

To expand the economic evaluation of potential oil-recovery techniques alternatives by including efficiency performance (exergy) and uncertainty (real option valuation) in the decision-making process.

As Rousseau (2012) argues: "practice-oriented research provides information about conditions and support practices that make scientific knowledge more useful. Its purposes are twofold: 1) to find solutions to practical problems and 2) to ease their adoption by identifying required support while reducing factors that work against their adoption or effective implementation". This research will contribute to scientific knowledge by applying the concepts of Real Option theory and Exergy analysis to oil-extraction techniques evaluation. And with the specific characteristics of this evaluation, contribute in the continuos process of generating theoretical body of knowledge along with future research that may confirm the findings from this research. Furthermore, this research will contribute to ease the adoption of project evaluation methods that take into consideration not only cashflows but also efficiencies in energy use and green-house-gas emissions and market uncertainties to managers in the oil industry, where new technologies and ever-increasing complex operations are the norm.

After conducting the literature review, presented in the following chapter, and recognizing the opportunity to improve the decision-making process of the selected oil production methods, the following research question is proposed:

How can real options and exergy analyses expand the cost-efficient selection of oil recovery techniques?

In order to answer this question, the following sub-questions are presented for obtaining the required knowledge to answer the main research question:

> *What are the considerations that need to be taken into account to apply exergy and real option analyses in oil-recovery techniques?*
>
> This sub-question aims to evaluate the way exergy and real-option analysis has been applied to industrial processes in the literature and how it can be used in oil-extraction techniques. A literature review will be performed, even though the examples directly applied to the oil industry are limited, several papers exist relating to other industrial processes. On the basis of this review, the analyses will

be applied to two selected techniques, taking into consideration the unique characteristics in equipment and fluids injected and produced.

How can real option theory and exergy evaluation be used for screening oil-recovery techniques?

Once the results are obtained from both analyses the preferred performance will be defined. Then, the performance of both techniques will be compared in order to stablish which has a better economic performance (NPV rule), which technique is more efficient (exergy analysis) and finally which has a better economic return adjusted for uncertainty (real options).

How does the conclusions obtained as a result of conventional economic appraisals differ from those obtained when including efficiencies and uncertainty in the evaluation of enhanced oil-recovery techniques?

In this question the comparative analysis between project economics and Exergy and Real Option analyses is presented regarding their characteristics and the results for the different oil-extraction techniques.

After analyzing the comparative analysis results, it will be possible to stablish the virtues and flaws of considering uncertainty and efficiencies in the appraisal of competing projects with the potential to assist the decision-making process.

1.2. Scientific and practical relevance

The scientific contribution of this research is twofold: First, the exergy and exergoeconomic theories are applied to oil-recovery techniques where no similar approach has been found in the literature for these specific projects. Second, real-option theory, both analytic and iterative, are also brought to the specific characteristics of oil-recovery techniques. The use of existing theories to new applications are recognized as a form of scientific contributions as discussed by Verschuren et al. (2010).

What can also be considered as a contribution, is the notion of expanding the standard evaluation of competing alternatives from only cashflow based criterias. The practical relevance of this research is bringing the notion of more inclusive evaluation approaches to managers. Additionally, the information provided by this analyzes can provide managers the tools needed to improve the applied thecniques in both efficiencies and economic performance.

1.3. Thesis outline

This thesis is structured as follows: Section 2 presents a brief description of the core concepts to familiarize the reader, along with the pertinent literature review regarding the current evaluation methods and their application to the screening of oil-recovery techniques; Section 3 describes the methodology to be pursued to answer the research questions; Section 4 presents the economic, exergy appraisal and the real options analysis for the waterflooding technique; Section 5 presents the evaluation of the polymer injection technique; Section 6 presents the comparative analysis between the results obtained from both techniques and finally, Section 7 discusses the main findings and provides recommendations for future research.

2. Theoretical background

2.1. Enhanced oil-recovery techniques

In order to extract oil volumes from underground reservoirs, where it is naturally stored, it is needed to conduct production projects. Initially, in most reservoirs, the oil is able to flow by itself from the bottom of the wells to the surface because reservoirs are naturally pressurized. After few years of production, a point is reached where production rates decline and intervention is needed to keep production at economic levels.

Waterflooding aims to increase the natural energy of the reservoir by injecting water through a well and displacing oil to a production well. The sweep of water allows to increase oil production in a reservoir from 15% to 40% depending on the reservoir and oil properties (Al-Saedi, et al., 2018). The final objective of this process is to inject a low-cost fluid into the reservoir and produce more oil by keeping a pressure differential between injector and producer wells. Additional costs to consider are pumping-energy requirements and water treatment.

Polymer injection increases the viscosity of the injected fluid and, as a result, increases the ability of the injected fluid to displace oil. When using this technique, the expected recovered volumes of oil are greater than water injection alone. However, energy requirements on the polymer handling and greater pumping energy needs must be considered along with the costs of the polymers. One additional effect of adding polymer to the injection of fluids is that with an increased ability to displace oil, less volume of water are needed and hence less will need to be treated after production (Sheng, 2013b).

2.2. Economic appraisal practice

Nowadays economic analysis is the main resource that managers use to evaluate oil-extraction techniques and to make investment decisions. This analysis usually takes the following steps:

- Forecast of additional oil to be produced during the project
- Forecast of oil prices at the time of production which will give a reference for expected gross income
- Forecast of capital expenditures or expected investments for the construction or upgrade of physical assets
- Forecast of operating expenses required to maintain oil production and day to day operations

In the oil industry, similar to other industries, technical projects are usually evaluated using NPV or ratio methods (Remer & Nieto, 1995a).

Net Present Value is the difference between the present value of cash incomes and the present value of cash costs over a period of time. The result of this computation gives an idea of the profitability of the project. The following formula is a general representation of the NPV:

$$NPV = \sum_{n=0}^{N} \frac{(Y_n - C_n)}{(1+r)^n} \tag{1}$$

where:

Y is the expected income from the additional oil produced
r is the discount rate
C the costs including Capex and Opex
n is the current year and *N* is the final year of project life

The discount rate is considered to be the opportunity cost of capital when choosing among project alternatives (Hard & Deren, 1991). The source of revenues for oil-recovery projects comes from the sale of oil barrels. The price for barrel is prone to vary widely along the years. Figure 4 shows three oil price scenarios proposed by the IEA where the three most important are: “current policies”, “new policies” and “sustainable development”.

The current policies scenario represents the oil price behavior expected if no shift occurs in the way governments procure their energy needs. The new policies scenario is based on the announced intentions in policy making from regulatory agencies to reduce the percentage of fossil-fuels in the energy mix. Finally, the sustainable development scenario assumes that the all necessary changes to achieve the UN sustainable development goals are fully conducted.

To observe the effect of different oil prices in the technique´s economics, the scenarios by the IEA will be used for the NPV calculations.

The following lines show a brief literature review with respect to oil-recovery techniques economic evaluation. There are several studies with aim in recent economic conditions (taxes, market conditions, management developments, etc.) (Ahmadi, Hasanvand, & Shokrolahzadeh, 2015; Hard & Deren, 1991; Tang, Song, & Cao, 2018; Vagenina, 2015 and Wei, et alii., 2015).

Ahmadi et al. (2015) investigate the performance of four gas injection techniques through numerical simulation. They perform a sensitivity analysis in the composition of the injected gas being N_2, CO_2, natural gas and flue gas. They estimate incremental oil produced as a result of the application of these techniques and with a single assumed oil barrel price they estimate revenues and NPVs for the different techniques. Their result shows that, in their criteria, the preferred gas injected would be flue gas as the simulations estimated up to 11% of extra oil recovered which is greater in comparison with the alternatives. Since the initial capital expenses and operating expenses are very similar for the injection of the four different gases the injection of flue gas is also preferred from the profitability point of view. It was observed that in this study uncertainties on oil price were not considered nor were the efficiency of the processes.

Tang et al. (2018) propose a methodology to evaluate risk inherent to tax policy changes. They evaluate China´s overseas investments and conclude that the current nations where they have allocated investment are riskier that other OECD countries. They are able to define the risk on investing in a given country through the use of a tax policy stability evaluation index. This paper evaluates uncertainty in a particular aspect but concludes that other sources of uncertainty should be contemplated during the evaluation of projects.

Vagenina (2015) proposes a methodological approach for creating an energy efficient project management in the oil and gas industry in Russia. She identifies the strategies followed by leading companies in the industry all over the world and proposes to prepare a strategy where natural gas play a bigger role as an energy source. This paper provides a bottoms-up approach on how to shift the strategy of a nations industry starting from the unit of projects.

Wei et al. (2015) provides an overview in the economic evaluation practice for oil-recover techniques selection in China over 296 onshore oilfields. They present a sensitivity analysis in a techno-economic evaluation where the variable parameters are oil price, CO_2 costs, project lifetime and tax policy. They find that with this approach more than 7.7 billion barrels of additional oil could be recovered.

Profitability evaluation methods do not consider process efficiency and therefore may prefer a highly inefficient and exergy intensive processes over more efficient ones based on merely explicit cashflows. Remer & Nieto (1995a;1995b) performed a compendium and comparison analysis of 25 different project evaluation techniques. They grouped the evaluation methods into five greater cathegories which are: net present value methods, rate of return methods, ratio methods, payback methods and accounting methods. As explained by the authors, these methods are widely used in all types of industries due to their simplicity and fast evaluation times, especialized knowledge is often not needed and the gathering of needed information is usually short. From these five categories only ratio methods such as benefit/cost ratio considers monetarized perseived cost of non-technical/tangible aspects like for example, the willingness to pay for a human life saved or noise reduction. And even such a method may not be objective on the process of valuating these perceived costs.

2.3. Exergy analysis

Exergy analysis has the potential to evaluate oil-production techniques objectively, considering their efficiency in relation to energy use and green-house gas emissions. Exergy is the maximum work potential of a system that is out of thermodynamic equilibrium with the environment (Smith, et al., 2016), exergy destruction can be considered as energy with the potential of performing useful work but that is instead wasted or dissipated into the environment. Unlike energy, exergy is destroyed because of entropy generation in real processes and due to irreversibilities, e.g. a burned piece of wood cannot be turned back into the original wood plus oxygen before being consumed by fire. The exergy analysis of oil-extraction techniques has the potential to pinpoint the weakest links of the full production cycle and therefore provides useful information for further optimization and improve its exergy efficiency.

Following Tsatsaronis (1993) guidelines we get:

$$E^{Tot} = E^{KN} + E^{PT} + E^{PH} + E^{CH} \tag{2}$$

where:

E^{Tot} *is the total exergy*

E^{KN} is the kinetic exergy or due to flow

E^{PT} is the potential exergy

E^{PH} is the physical exergy as a result of differences in pressure and temperature with the environment

E^{CH} is the chemical exergy due to the composition of the stream

It is important to note that the analysis is conducted for each subsystem in the entire process. Then, it is possible to obtain the exergy destruction in each subsystem and identify the most inefficient part of such process and compare one entire process with another competing option.

De Oliveira and Van Hombeeck (1997) present an analysis of oil and gas processing in a typical Brazilian platform considering common operating conditions of the area. Their analysis pointed that up to 70% of exergy was generated in the heating and compression processes of the platform while the remaining 30% can be attributed to processing of oil, gas and water. The paper concludes with advising more efficient heating and power generation processes but does not analyze technique selection implications.

Finnveden and Ostlund (1997) calculate exergy efficiencies in natural resources harvesting by applying a life cycle assessment on the extraction of minerals. They analyze how system boundaries affect exergy results and propose to use a whole mineral ore as system boundaries for this particular natural resource. This study although quite specific, sheds light on sensibilities to exergy analysis.

Nguyen et al. (2013) make an exergy analysis for typical North Sea platforms considering operating conditions predominant in the region. Their study showed that up to 65% of exergy generation or wasted energy is found in the power generation to run the platform and on the waste heat recovery system. The other 35% can be attributed to the processing of oil and gas. They conclude by advising on optimizing the pinpointed processes. However, they only consider a single production mechanism and do not discuss the relevance of such results for the decision-making process.

The existing literature of exergy analysis is limited in the oil and gas industry. A review of this literature reveals that none of the studies linked their findings with the economics of projects or considering the uncertain nature of the industry. Exergo-economics combines, at the level of system components, thermodynamic evaluations with economic concepts (Tsatsaronis & Pisa, 1994). Some studies were found about the application of Exergoeconomics to other industries and processes.

Kwon et al. (2001) performed an exergoeconomic analysis of a gas turbine cogeneration system. The authors approach the analysis by performing an exergy balance of the entire system and stablishing cost equations per system. They then compared the results with a new simplified methodology where instead of analyzing the entire system as a whole they assigned a unit exergy cost to each subsystem. They conclude that in both methodologies the unit cost of products is highly dependent on the capital expenses of the subsystem units and then in the initial design and configuration of the system.

Tsatsaronis and Park (2002) evaluate a cogeneration system and focus their study on defining the exergy destruction. They then move to classify the total exergy destruction into avoidable (possible to reduce/eliminate through investment) and unavoidable exergy destruction (maximum practical efficiency obtainable). They conclude that for each component of a typical gas turbine cogeneration system it is possible to avoid from 45 to 79% of the costs incurred due to exergy destruction. They move to recommend further research on the definition of unavoidable exergy destruction.

Rosen and Dincen (2003) analyze three different electricity generation methods: coal-fired, oil-fired and nuclear and define the relation between exergy losses and capital costs. They found that for the different processes a relation exists between the exergy loss to cost ratio of a single unit and the overall ratios considering the whole system but this relation is not present when considering energy as the measuring unit. They argue that this means that devices are designed to have an overall optimal design by balancing the thermodynamic and economic characteristics between components. They end by advising on further research on different technologies before generalization can occur due to the specific nature of the case studied.

As see in this literature review the studies performed in the oil industry are limited and those present focus on the downstream sector. This thesis contributes to the literature by bringing exergy analysis to the upstream oil industry and more specific to the waterflooding and polymer injection oil-recovery techniques.

2.4. Real option valuation

Real option (RO) theory refers to the application of financial options assessment to non-financial or technical projects. It can be considered as the flexibility to change from one action path to another, to postpone a strategy or even abandon a project. In contrast with cashflow based evaluation, RO does not consider a fixed given scenario where "perfect foresight" (e.g. the oil price will behave exactly as assumed) is considered. Instead, RO captures uncertainty through the consideration of many scenarios and their given probability distribution.

RO Theory can be used to assess investment decisions and, in this sense, to evaluate different possible techniques. There are different ways to calculate the "options" of a project, from partial differential equations, threes and lattices and simulations. In this thesis, in order to analyze differences and similarities, two different frameworks will be used. The first one is, the framework proposed by Dixit & Pindyck (1994) in relation to investment with uncertainty. This approach follows an analitic representation of the option value through a differential equation. The second framework is that proposed by Mathews (2007) where several oil price scenarios are modeled through a random walk process following a Brownian motion (Durrett, 2000). As discussed by Fernandes et al. (2011), there are different frameworks to solve real options, but the differential equations and iterative approaches are the most commonly used.

For the analytic approach, the following set of equations will be adapted to the specific technique characteristics:

$$F(V) = A_1 V^{B_1} \tag{3}$$

where:

F(V) is the option value of an unexercised option.
V is the value of an oil barrel
A_1 and B_1 are values calculated considering the rate of interest and the oil-price standard deviation σ.

with these equation, F(V) is calculated and can be used to further calculate the optimal timing of investment.

For the iterative approach, the value of the option is defined as the mean of the possible NPVs capturing the effect of uncertainty in the final economic assessment. This relation is expressed by:

$$RO\ value = \frac{\sum_{e=1}^{E} NPV_e}{E} \tag{4}$$

where *e* is an specific iteration and *E* is the total number of iterations.

A brief description of relevant literature on RO follows.

Correia et al. (2008) propose a methodology to analyze project options under cost possibilities for carbon emissions. This type of analysis could be performed as well in oil-extraction projects for the oil price.

Martinez-Cesena et al. (2013) present a critical review of RO theory, its state of the art, and its applications to energy generation projects. Among their review the use of real option theory on valuating uncertainty related to CO_2-emmissions tax, results of interest and could show a profitability envelope considering the mentioned uncertainties.

Dixit & Pindyck (1994) propose a framework with which it is possible to obtain the option value of undertaking a project, given certain conditions, and the most efficient timing to conduct the project as uncertainties unfold. Similarly, this framework could be useful to define the value of using a specific oil-extraction techniques in relation to uncertainties like oil price.

Welkenhuysen et al. (2017) analyzes the application of CO_2 enhanced-oil-recovery technique in two fields of the North sea. In their techno-economic analysis they consider uncertainty in markets, policy, geological and technological uncertainties. They use imperfect foresight and real option analysis to make investment decisions with more realistic considerations. They also analyze the difference of considering stand alone field projects versus the possibility of clustering some fields in a bigger project. They conclude that considering fields as stand alone projects may undervalue the projects. By including uncertainty in their simulations they are able to stablish a range from -6 €/bbl loss to 30 €/bbl profit depending on the development of the uncertainties. Similarly, they stimate an extra 5 €/bbl generated when considering cluster projects in comparison with stand alone field developments. The authors conclude their analysis by recommending the addition of more sources of uncertainty to the valuation of projects to make decisions with more realistic stimates.

Matthews (2007) in collaboration with Daatar propose the Daatar-Mathews method to evaluate real options for projects. They work with the company Boeing to analyze a previously deemed marginal project and consider multiple scenarios for the development of the project. They perform Monte Carlo simulations on the possible outcomes and advice to generate up to thousand different scenarios. They then recommend to obtain the mean of the NPVs obtained in the simulation. This average should contain a more informed estimate that the regular NPV rule. With this method a project previously deemed uneconomic is recategorized as feasible.

Armstrong et al. (2004) analyzed the possibility to assess the option value of obtaining extra information before developing an oilfield. They explore the options to obtain information from a production logging tool and then perform a workover or directly perform the workover without additional information. They make use of Bayesian updating to overcome the symmetry limitation of multivariate normal frameworks. They found, contrary to what is expected, that the option value of gathering additional information before intervention is lower with higher oil prices. They argue that this counterintuitive result is the consequence of considering the obtained value as incremental to the base case and not as a standalone value.

Santos et al. (2014) evaluates a hydro-plant through traditional methods and through ROs. They use a binomial tree to analyze the effect of uncertainty in their case study, where the source of uncertainty is the value of power. They conclude that ROs have the advantage to provide management with the ability to influence the final value of the project through the options they decide to exercise. They recognize in their analysis the need to include more uncertainties, e.g. the level of power generation, costs, demand and the cost of postponing the exercise of an option.

Fernandes et al. (2011) on the other hand, perform a review on the current state of the art of ROs applied to the evaluation of renewable energy sources. In their study they recognize that uncertainty comes from different fronts. They mention uncertainties tied to the variability of natural sources, support schemes, learning curves and markets. They additionally provide recommendations on future research in the field of ROs and renewable energy industry. They call for research in the application of ROs in photovoltaic industry and biomass as in their view few research can be found.

Gedes et al. (2016) perform RO analysis to an oil exploration and production project. With the support of a company they analyze the options to proceed or abandon the project at a given time. For this study, they consider uncertainty in the reserve size and in the price of oil. They conclude that the RO analysis turns the project from uneconomical to economically viable option when the option to abandon is introduced. They recommend that future research with application to oil exploration and production should be applied with a clinical approach, in order to capture the specific details of each project.

As seen in this literature review there exist some studies on the applicability of real options to the oil industry and even to oil-recovery projects. The contribution of this thesis to the literature is to evaluate the waterflooding and polymer injection with a real-option analytic approach and with an iterative approach. The application of both approaches allows to distinguish the differences and the needed considerations for the application of real-option theory in oil-recovery techniques.

3. Methodology

In this section the methodologic approach to answer the research questions and meet the research objective will be discussed. Section 3.1 presents a description of the framework which is a representation of the most important phases in this thesis.

3.1. Research framework

In this thesis research, first, the economic estimation of oil-recovery techniques is performed. Then, it follows an exergy analysis that can be used to evaluate and improve the efficiency of the technique. Finally, a study of the effects of uncertainty will be performed. The research will start with the study of water flooding and a second oil-recovery technique, polymer injection. The exergy analysis and the real option valuation will be compared to the economic evaluation of these recovery mechanisms and their consistency/inconsistency will be discussed. Next, conclusions will be drawn with regards to what is learned during the application of these analyses.

Figure 5 show a schematic representation of the research framework for this thesis.

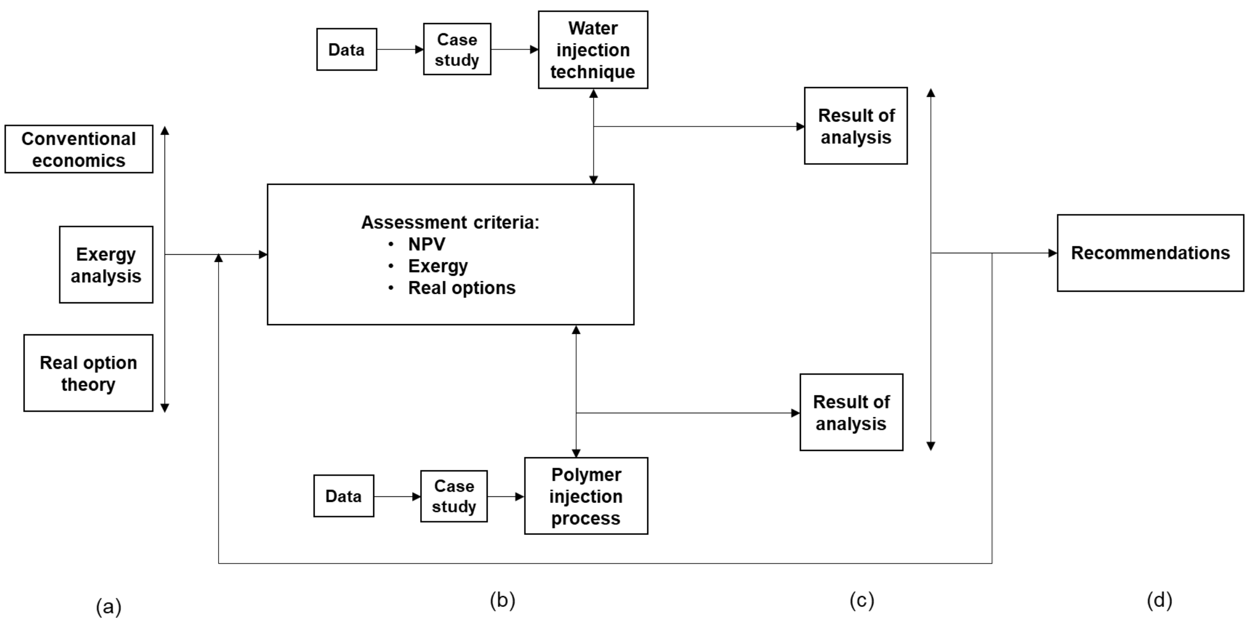

Figure 5. Research framework.

In step (a) the practice of conventional economic analysis like Net Present Value (NPV), along with the analysis of the quality of energy in industrial processes, or exergy analysis, and real-options are used to propose an evaluation criterion for oil-extraction techniques selection that combines the mentioned theories. In step (b) data provided by the external advisor is analyzed and a case study is defined as described in the next section, then, two oil-recovery techniques are assessed with the mentioned criteria. Each technique will be simulated by the external advisor and the results will be used as input in this thesis to analyze first economically, then with an exergy analysis and finally with a real options valuation. In step (c) the results of this confrontation are studied and in step (d) a series of recommendations are issued. This is an iterative process and feedback from the confrontation will be used to refine the assessment criteria.

3.2. Case study

The case study considered for this thesis project is the simulation of a small field where two different oil-recovery techniques are assessed with the proposed criteria. Oil fields usually have hundreds of wells and depending on the specific conditions can be of thousands (Wheaton, 2016). On the other hand, it is common practice to evaluate the viability of a project at small scales to observe the response of the oil-bearing reservoir to the treatment. Similarly, such small-scale projects are also simulated for preliminary estimations. In this case study eight injection wells and eight producing wells in a reservoir will be simulated over a period of twenty years.

The oil price will be considered to shift according to the IEA scenarios (International Energy Agency, 2017) for the standard NPV analysis. For the Real Option analysis, the oil price will be simulated with a Monte Carlo approach where oil price increments (or decrements) follow a Wiener Process, a continuous-time stochastic process. The reason to simulate the oil-price behavior instead of considering the IEA scenarios is because as describe in section 2.2, these scenarios only consider the possible effect on oil demand as a result of new policies adopted by the government. They do not include supply forces or speculative effects from traders, among others. For this reason, a simulation with a random walk is expected to be representative of additional unforeseen uncertainty sources.

The estimated oil and water volumes from the simulation are used as input in this thesis to perform the economic appraisal, exergy and real option valuation. Figure 6 is a representation of the system when using the waterflooding technique.

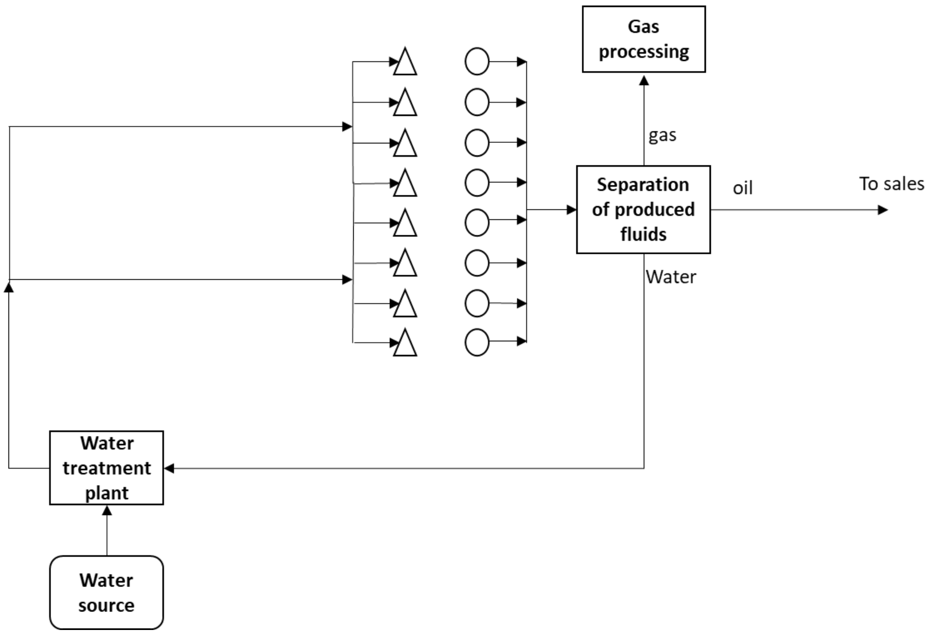

Figure 6. Waterflooding system representation. Triangles are injector wells. Circles are producing wells.

For the case of polymer injection technique, the configuration will be like that of the waterflooding with the addition of equipment for the treatment of the oil/polymer/water mixture and special mixing facilities. In the following sections a detailed system representation is provided for both techniques.

In order to perform the simulation, the external advisor considered a simplified streamline methodology in which the Buckley-Leverett theory (van den Hoek, 2004) is used to estimate the volumes of oil recovered.

Table 1 shows the reservoir properties considered by the external advisor while simulating the flooding techniques.

Table 1. Reservoir parameters for the oil-recovery simulations

Layer Thickness	50	m
Depth	700	m
Water density	1000	Kg/m^3
Oil density	885	Kg/m^3
Delta P0	10000000	Pa
Porosity	0.3	
Pore Volume	9.50E+05	m^3
Oil originally in place	8.64E+05	m^3

Table 2 shows the parameter results obtained by the waterflooding simulation:

Table 2. Result parameters provided from waterflooding simulation

Pattern time (yrs)	f_w	Q_o (m^3/s)	Vol oil (m^3)	inj vol (m^3)	cum oil (m^3)	cum water (m^3)

Where f_w is the fraction of water flow with relation to total flow, Q_o is the oil flow rate produced, *Vol oil* the volume of oil produced in one year, *Inj vol* is the volume of water injected in one year, *cum oil* is the cumulative volume of oil produced from year zero to the year of consideration and *cum water* is the cumulative injected water. The mentioned parameters will be used as input for this thesis to perform the economic, exergy and real option analyses.

In the case of the Polymer flooding technique the results will contain the same parameters in *Table 2* plus the amount of polymer injected per pattern time. The simulation results can be found in Appendix A for the waterflooding and Appendix J for the polymer injection.

It is important to note that for the polymer injection first a period of two years only water is injected and is thus identical to the waterflooding technique. Then, from year 3 onwards polymer injection begins which increases oil production and as a consequence increments in NPV, exergy and real-option values. In this thesis first the two techniques are analyzed in a standalone fashion for performance and improvement analysis. Then, considering the mentioned incremental values, a comparative analysis is performed considering the difference in behavior after year 3 for both techniques.

3.3. Analyses methodology

The required data needed to perform the analyzes will come from the external advisor from documents such as: business cases, feasibility studies, project plans, operational project documentation, final reports, lessons-learned, recommendations reports, fluid properties reports and literature on similar projects.

It is noteworthy to mention that the objective of this research is to draw recommendations for the evaluation of the oil-extraction techniques and does not intend to stablish the "best" option from the two processes analyzed, as every project in real practice will present differences in its characteristics and most likely the results would vary.

A brief description of the analyses is presented next.

3.3.1. Net Present Value

For the NPV analysis two different parameters will be varied considering perfect foresight: different oil price scenarios and different discount rates. Table 3 shows the nine situations that will be considered. The oil price scenarios will be obtained from estimates from the IEA as seen in Figure 4. The discount rates, following the literature on NPV estimates in the oil and gas industry (Harris & Ohlson, 1987; Wei, et al., 2015; Qiu, et al, 2015), will be assumed to be 10% and five percentile points more and five percentile points less to analyze the effect on the final NPV.

Table 3. Sensitivity conditions for the standard NPV analysis.

Sensitivity	**Discount rate**		
IEA Oil Price Scenarios	IEA scenario 1, 5% discount rate	IEA scenario 1, 10% discount rate	IEA scenario 1, 15% discount rate
	IEA scenario 2, 5% discount rate	IEA scenario 2, 10% discount rate	IEA scenario 2, 15% discount rate
	IEA scenario 3, 5% discount rate	IEA scenario 3, 10% discount rate	IEA scenario 3, 15% discount rate

Considering a given oil price behavior during the life of the project, an expected undiscounted revenue can be obtained following the formula:

$$B_n = cum\ oil_n \times expected\ oil\ price_n \quad (5)$$

where *n* represents a specific year and *B* the benefit obtained from the sale of the cumulative oil produced. Figure 4 shows the expected oil price given different policy developments. The value per year is the expected average price along that particular year. The detailed table with price per year for the three different IEA scenarios can be found in Appendix B.

Capex is then estimated by considering investment cost using the following equipment for the waterflooding technique:

Table 4. Facility components considered for the Capex of waterflooding process

Unit	Item
Separation of produced fluids	FWKO, Multiphase separator
Separation of produced fluids	Booster Pumps
Separation of produced fluids	Export pumps
Separation of produced fluids	Heaters
Separation of produced fluids	Dehydration Tanks

Water treatment Plant	Nutshell Filter
Water treatment Plant	Backwash System
Water treatment Plant	Tanks
Water injection	Pumps
Water injection	Manifolds
Water injection	Distribution system
Production Gathering	MSVs
Production Gathering	Distribution system
Producer well cost	
Injector well cost	

The sizing of the equipment and the costs are presented in section 4.1.

The external advisor has provided a cost report of a waterflooding project with 200 wells which can be found in Appendix A and B. For this big scale operation, the reservoir conditions are considered to be the same as the ones presented in Table 1. In order to estimate capital expenditures for the case study in this thesis, the given large-scale costs are scaled down following the formula:

$$Cost_2 = Cost_1 \left(\frac{Size_2}{Size_1}\right)^a \quad (6)$$

where:
$Cost_2$ is the capital cost of the scaled item
$Cost_1$ is the capital cost of the original size item
$Size_2$ is the new unit size
$Size_1$ is the original size of the item
a is the scale factor

The scale factor a comes from the following relation:

$$a = \frac{\log Cost_2 - \log Cost_1}{\log Size_2 - \log Size_1} \quad (7)$$

In this thesis an average scale factor of 0.6 is used for the calculations based on the estimates obtained from costs reports by the external advisor. For every equipment the size of the item will not be considered as the number of wells but the operating size of the equipment. For example, in the case of the pumps the operating flow rate capacity will be considered as this changes with the reservoir requirements and not with the number of wells drilled. The reservoir requirements can be found in Appendix A and *Table 1* shows its most relevant characteristics.

Opex will then be estimated by considering the average cost per barrel ($/bbl) of oil produced and the cost per barrel of water produced obtained from the literature (Miller, 2003; Macary, et al., 2000; Wei, et al., 2015). It is important to mention that the expenditure of energy driving the considered equipment (defined as Enex) will be considered as an independent Opex category. Later in section 3.3.7 it will be explained further that the Capex and Opex, excluding energy cost, will be used to calculate a Z factor used in exergoeconomic analyzes while the Enex represents a different factor.

*Table 5. Opex cost per unit of output. (*Miller, 2003; *Macary, et al., 2000; Wei, et al., 2015;* European Union Statistical Office, 2018)

Concept	Expense	
Average processing and injection cost of water	1	$/bbl
Average cost of producing and processing oil	2.5	$/bbl
Average cost per energy unit	0.106	$/kWh

These average costs include labor, maintenance and consumables needed. The produced volumes obtained from the simulation will then be multiplied for the average cost per unit and the Opex will then be estimated. In this sense there will be three Opex components: Opex from handling oil production, Opex from handling water production and the Opex from energy requirements or Enex. The formula (8) is a representation of total costs.

$$C_n = Capex_n + Opex_{oil,n} + Opex_{water,n} + Enex_n \tag{8}$$

Again, *n* stands for a specific year. The component *Enex* is calculated by estimating the energy requirements for every equipment per year. Then, the average cost per unit of energy found in Table 5 is used to define the total costs derived from the energy needs. The energy requirements calculations for every piece of equipment can be found in section 3.3.5.

An undiscounted cashflow will then be calculated by subtracting total costs to the expected revenues.

$$uCashflow_n = B_n - C_n \tag{9}$$

The rationality for disaggregating undiscounted cashflows from their present value is for easily modifying the discount rates, if needed, and being able to visualize the simple discount rate sensitivity analysis.

Three different discounted factors will then be computed considering 5%, 10%, 15% as discount rates for each year.

$$DF_n = \frac{1}{(1+r)^n} \tag{10}$$

Discounted cash flows can then be obtained by multiplying the undiscounted cashflows by the discounted factors.

$$PV_n = DF_n \times uCashflow_n \tag{11}$$

A summation of the discounted cashflows yields the NPV of the project.

$$NPV = \sum_{n=0}^{N} DF_n \times uCashflow_n \tag{12}$$

where *N* represents the total lifetime of the technique. In this thesis the life of the project will be considered over when the estimated cashflows for a particular year return negative values.

3.3.2. Considerations for the standard NPV analysis for Polymer flooding technique

The same methodology discussed in section 1 will be followed to perform the standard NPV analysis of the polymer injection technique. Some differences must be considered and will be outlined in this section.

For the polymer injection technique additional Capex is expected specially in the preparation of the fluid to be injected. For mixing the polymer with water, a mixing plant is required. Additionally, most polymer products are sensitive to oxygen which require a Nitrogen blanket generator to keep the integrity of the fluid before injection (Sheng, 2013a).

In the case of the Opex, the biggest difference lies in the additional costs from the polymer product, even thought, also additional energy requirements must be considered due to increased oil production. As Temizel, et al. (2017) describe, the most used polymer products in oil recovery applications are Xanthan gum, a biopolymer, and HPAM a synthetic polymer. While both present high temperature resistance, Xanthan gum is expensier and can present plugging problems during injection. In this thesis the polymer considered to be injected is the Hydrolyzed Polyacrylamide (HPAM). From a literature review an average cost per kg of the product is obtained.

Another difference in Opex present in this technique is the treatment of water, as this product cannot yet be recycled for reinjection the fluids must be treated for disposal. Al-Murayri et al. (2018) and Temizel et al. (2017) describe the economic aspects of polymer flooding and the average costs per barrel and kilogram presented by these authors are used to build Table 6.

Table 6. Opex for polymer Injection (Al-Murayri, et al., 2018; Temizel, et al., 2017).

Concept	Expense	
Average treatment and injection cost of water and polymer mix	2	$/bbl
Average cost of producing and processing oil	2.5	$/bbl
Average cost of injected polymer	3	$/kg

3.3.3. Exergy analysis

Considering the waterflooding technique nature and the components in Table 4, the component layout for the waterflooding technique is presented in Figure 7. On the lower-left side of the system representation, the water source is shown. The injection-pumps push the water down the injection wells pushing additional oil through the production wells. The production streams will contain water, oil and gas. The fluids need to be separated and first they flow through a separator and a heater. After these pieces of equipment, the present gas is separated and send to procesing. Water in its mayority is separated from the oil and send to water treatment but a small portion remains emulsified to the oil. The produced oil is flown to dehydration tanks where the remaining water is separated and sent to water treatment. The oil is then sent to sales and water is treated for reinjection.

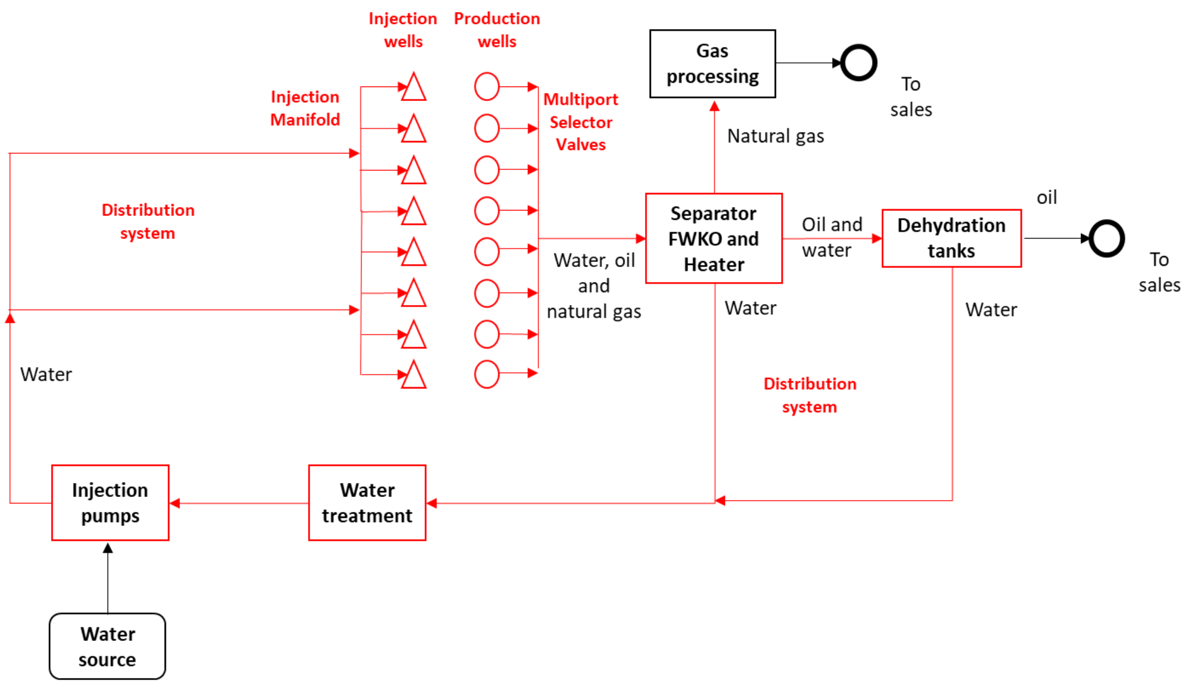

Figure 7. Waterflooding system representation. Red color represents the relevant Exergy inputs needed to produce and process the additional oil.

Following the recommendations of Tsatsaronis (1993) and De Oliveira & Van Hombeeck (1997) the exergy analysis is divided into two main categories: the exergy of the fuels and the exergy of the products. This distinction helps to analyze the exergy invested as fuel in the energy carriers (pumps, heaters, etc) and the exergy contained in the material streams as products of the energy carriers and the interaction with the oil producing reservoir (heat and inflow of oil and gas).

Equation (13) shows that the Exergy of the fuel will be equal to that of the product plus any Exergy destroyed in the system. Exergy destruction includes the internal exergy destruction due to irreversibilities and the external exergy destruction due to mass transfer. Since no leakage of materials to the environment is considered, only the internal exergy destruction is analyzed.

$$Ex_{fuel\ i} = Ex_{product\ i} + Ex_{destruction\ i} \tag{13}$$

where i represents the specific component or equipment from the layout in Figure 7.

From equation (13) we get:

$$Ex_{product\ i} = Ex_{fuel\ i} - Ex_{destruction\ i} \tag{14}$$

3.3.4. Product Exergy

The Exergy of the product will be given by:

$$Ex_{Product\ system} = \sum_{i=1}^{I} Ex_{product\ i} \tag{15}$$

$$Ex_{product\ i} = Ex_{j,\ out}^{Tot} - Ex_{j-1,\ in}^{Tot} \tag{16}$$

Where *i* again represents a specific equipment and *I* the last considered equipment in the technique. So, the Exergy product of the whole system will be the summation of the Exergy product of every equipment *i*. For the individual calculation of the exergy product, the total exergy of the material stream coming out (*j*) from the energy carrier is subtracted to the exergy of the material stream coming in (*j-1*). In other words, the exergy of the product is the change in total exergy of the material streams when it goes through an equipment.

The total exergy of a material stream *j* is given by:

$$Ex_j^{Tot} = Ex_j^{KN} + Ex_j^{PT} + Ex_j^{PH} + Ex_j^{CH} \tag{17}$$

Where the kinetic, potential, physical and chemical exergy of the material stream are represented. *j* again represents the material stream.

The Kinetic Exergy of a system can be defined as the Kinectic Energy of the stream as Kinetic Energy can be converted to work entirely (Dincer & Rosen, 2000) and is given by:

$$Ex_j^{KN} = \frac{1}{2} m_j v_j^2 \tag{18}$$

where the mass and the cuadratic speed of the stream is considered. Since the mass and the speed of the streams in and out of the components are similar, the Kinetic Exergy is considered negligible in this thesis.

The Potential Exergy can similarly be considered as the Potential Energy and is described as:

$$Ex_j^{PT} = m_j \times g \times h_j \tag{19}$$

which consideres the mass, the gravity constant and the height in relation to the ground level as reference. Since most of the components are at ground level and the injection point of the well is considered to be at the same level of the production well, the potential exergy is also deemed negligible for this thesis. As Dincer and Rosen (2000) argue, the kinetic exergy wil be of importance in high velocity processes e.g. in turbines design. The potential exergy in processes were difference in altitude is relevant as in hydropower plants. Simmilarly, Nguyen et al. (2013) in their exergy analysis in a oil offshore platform in the North consider the potential and kinetic exergy negligible in comparison to the physical and chemical exergy.

Considering that in this technique the potential and kinetic exergy are negligible, only the physical and chemical exergy of the material stream will be included in the total exergy. The physical Exergy responds to temperature and pressure differences from the reference environment and is given by:

$$Ex_j^{PH} = m_j\left[\left(h_j - h_0\right) - T_0\left(S_j - S_0\right)\right] \tag{20}$$

where *m* is the massflow, *h* the specific enthalpy of a material and *S* the especific entrophy of the material. The suffix *0* states the specific enthalpy or entrophy of the material at standard conditions (293°K, 101 325 Pa) considered as the reference environment. The specific enthalpies and entropies of each stream component at inlet and outlet conditions are calculated using the Peng-Robinson equations of state module in the DWSIM open source process simulator.

For the chemical exergy of a material stream, the data obtained by Szargut (2007), Rivero & Garfias (2006) and Stougie (2014) for chemical exergy values are used to estimate the chemical contribution to the total Exergy.

$$Ex_j^{CH} = m_j(Exv_j) \quad (21)$$

where the mass and the exergy per every kg of a specific material is considered. Even though no chemical reactions are present between the components and bewtween the components and the environment, the chemical exergy is useful to illustrate the addition of oil and gas from the reservoir to the material streams. This can be considered as exergy coming into the system along with the increase in temperature at the reservoir. Even though in real life applications some water is lost in the reservoir, in this thesis this effect is assumed to be neglectable.

In order to portrait a clearer picture of the exergy product, the needed calculations for an equipment will be described with the help of equations (16), (17), (20) and (21).

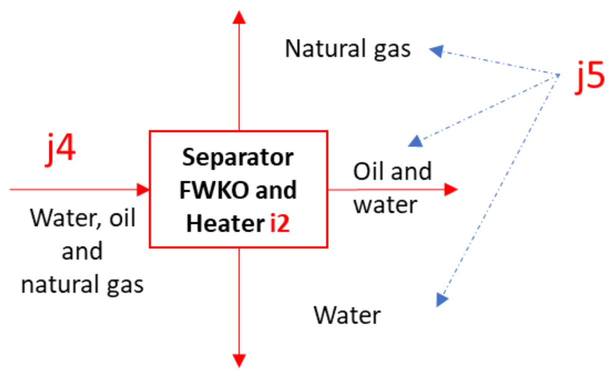

Figure 8. Material streams in and out the Separator and Heater unit.

From Figure 7 and Figure 8 the separator/heater unit will be analyzed; for this example consider this equipment as *i2*. In order to calculate the Exergy product of this energy carrier, first, the total Exergy of the material stream coming out and into the equipment must be calculated. Consider the material stream coming in labeled as *j4* and the material stream coming out of the energy carrier as *j5*. Then:

$$Ex_{product\ i2} = Ex_{j5}^{Tot} - Ex_{j4}^{Tot}$$

Then, considering only the physical and chemical exergy as components of the total exergy, we get:

$$Ex_{j4}^{Tot} = Ex_{j4}^{PH} + Ex_{j4}^{CH}$$

$$Ex_{j4}^{PH} = m_{j4,w}[(h_{j4,w} - h_{0,w}) - T_0(S_{j4,w} - S_{0,w})] + m_{j4,o}[(h_{j4,o} - h_{0,o}) - T_0(S_{j4,o} - S_{0,o})] + m_{j4,g}[(h_{j4,g} - h_{0,g}) - T_0(S_{j4,g} - S_{0,g})]$$

$$Ex_{j4}^{CH} = m_{j4,w}(Exv_w) + m_{j4,o}(Exv_o) + m_{j4,g}(Exv_g)$$

where the suffixes *w*, *o* and *g* stand from water, oil and gas materials present in the stream.

Similarly, for the material stream coming out, or *j5,* we get:

$$Ex_{j5}^{Tot} = Ex_{j5}^{PH} + Ex_{j5}^{CH}$$

$$Ex_{j5}^{PH} = m_{j5,w}\left[\left(h_{j5,w} - h_{0,w}\right) - T_0\left(S_{j5,w} - S_{0,w}\right)\right] + m_{j5,o}\left[\left(h_{j5,o} - h_{0,o}\right) - T_0\left(S_{j5,o} - S_{0,o}\right)\right] + m_{j5,g}\left[\left(h_{j5,g} - h_{0,g}\right) - T_0\left(S_{j5,g} - S_{0,g}\right)\right]$$

$$Ex_{j5}^{CH} = m_{j5,w}(Exv_w) + m_{j5,o}(Exv_o) + m_{j5,g}(Exv_g)$$

Finally, the Product Exergy of component *i2* will be the subtraction of the total exergy in *j5* minus the total Exergy in *j4*.

3.3.5. Fuel Exergy

The Exergy fuel is the useful energy that a piece of equipment exerts to the material streams in order to perform its intended purpose. The Exergy fuel can be mechanical, thermal or electrical power that needs to be invested (Tsatsaronis G. , 1993). Equation (22) illustrates these notion; the calculation of the Exergy fuel will be different for every piece of equipment as will next be described.

$$Ex_{fuel\,i} = W_i \tag{22}$$

Following Figure 7, the fuel exergy calculation is described per equipment starting with the water injection pump. For the pumping of water, given the provided simulation results from Appendix A, the required volumes of water to be injected can be found and used to stablish how much exergy fuel this tasks consumes. The simmulation considers the equation proposed by Craig (1971) where the injection rate is described as:

$$Q = \frac{h \times k \times \Delta P}{\frac{\mu_w}{k_{rw}} \ln\frac{r}{r_w} + \frac{\mu_o}{k_{ro}} \ln\frac{r_e}{r}} \tag{23}$$

where:

Q = volumetric water injection rate
h = formation thickness
k =absolute permeability
μ = fluid viscosity

kr = relative permeability
r = radius
ΔP = pressure differential between well and reservoir

Considering the relative permeability to be the fraction of flow where more than one fluid is flowing in the reservoir in comparison with the absolute permeability.

Having the injection flowrates, next it is needed to calculate the power the pump needs to deliver in order to maintain the pressure in the reservoir, movilize the water and, in a piston like fashion, push the oil present in the formation. The power or work per unit of time used in one year gives the exergy fuel invested to pump in that particular year.

Figure 9 shows the components that are taken into account for the fuel exergy of the injection pump.

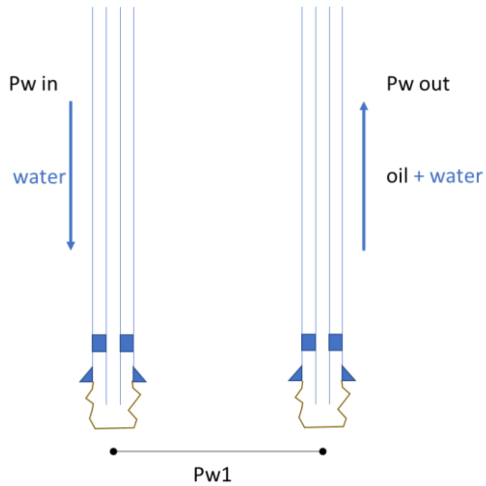

Figure 9. Pump fuel exergy illustration.

Pw1 which represents the power needed to mobilize the water and oil in the porous media from the injector well to the producing well is given by:

$$Pw_1 = Q \times \Delta P \tag{24}$$

The power needed to move the fluids vertically down the injector well and up the producing well considering the different fluids (only water injected and oil and water produced) is expressed by Pw_{in} and Pw_{out} respectively:

$$Pw_{in} = -Q \times \rho_{water} \times g \times d \tag{25}$$

$$Pw_{out} = Q \times g \times d \times [(f_w \times \rho_w) + (1 - f_w) \times \rho_0] \tag{26}$$

where f_w is the fraction of water in the material stream and ρ represents the density of the fluids.

Having obtained P_{w1}, Pw_{in} and Pw_{out} then the fuel exergy used for the pumping of fluids can be calculated by:

$$Pw_{tot} = Pw_1 + Pw_{in} + Pw_{out} \tag{27}$$

$$Ex_{fuel\ pump} = P_{tot}(t_n) \tag{28}$$

where *n* is the time period considered for the calculation.

The second energy carrier shown in Figure 7 in the direction of flow, and after the injected water and produced oil and gas come to the surface through the producing wells, is the heater and separator. The purpose of the heater is to warm the fluids enough to facilitate the separation of the oil and gas.

For this case study, a normal geothermal gradient down the wells is assumed (30°C every 1km down) (Turcotte & Shubert, 2002) which means that the injected water and also the produced oil and gas will return to the surface with a temperature of 55°C, greater in comparison to the environment considered as 25°C. For this thesis it is also assumed that the objective of the heater is to raise the temperature of the produced fluids to 75 °C as a result of the oil properties considered in the simulation performed by the external advisor. In practice, depending on oil properties, this temperature can be that up to 90 °C (Nguyen, et al., 2013).

In order to calculate the fuel exergy of the heater the following relation is used:

$$Ex_{Heater} = m \times C_p(T_2 - T_1) \tag{29}$$

where the heat capacity of oil, gas and water is considered along with the temperature when entering the heater and leaving the heater.

After the separation process, gas is send to processing, water for treatment and oil to dehydrator tanks. In this piece of equipment an electrostatic field is maintained to promote the coalecesnce of water droplets emulsified in the oil. Depending on the characteristics of the produced fluids, from 5% up to 20% of water can be present emulsified in the oil after initial separation (Eow & Ghadiri, 2002). In this thesis, 5% of emulsified water is asumed and the fuel exergy is calculated following the equation:

$$Ex_{Dehydrator} = produced\ fluids\ \times exergy\ per\ mass \tag{30}$$

The water treatment contribution to fuel exergy in the water flooding process is estimated by:

$$Ex_{w\ treatment} = volume\ produced\ water\ \times exergy\ per\ volume\ unit \tag{31}$$

Reverse Osmosis is considered to be the method for treating the produced water, where suspended solids and salts are removed. The treated water is then recycled into the well through the injection pumps and the circuit from Figure 7 begins anew.

In order to account for unforeseen exergy fuel from utilities an “Other Exergy” was included in the calculations in Appendix D following the literature (De Oliveira & Van Hombeeck, 1997; Nguyen, Pierobon, Elmegaard, & Haglind, 2013).

It should be noted that the described calculations for exergy fuel is in practice the needed energy the pieces of equipment need in order to perform their function. If the energy requirements are known and a single cost per kWh is considered as shown in Table 5, then it ispossible to estimate the opex from energy requirements or Enex.

3.3.6. Exergy ratios

Once the product exergy and fuel exergy are estimated, the exergy destruction is derived from equation (14). The exergy destruction can point to the energy carrier with the biggest inefficiencies and, in its aggregated form, can be used as a base to compare competing techniques with regards to their exergetic efficiency.

$$Ex_{destruction\ i} = Ex_{fuel\ i} - Ex_{product\ i} \tag{32}$$

The exergy destruction ratio is a measure of the equipment contribution to the total exergy destruction. This ratio allows to compare the efficiency of each component within the technique or similar energy carriers in different techniques (Tsatsaronis G. , 1993). The exergy destruction ratio is given by:

$$y_{Di} = \frac{Ex_{Di}}{Ex_{Dtotal}} \tag{33}$$

The exergy recovery factor is a ratio that relates how much exergy is invested as fuel and how much is destroyed, to how much exergy is recovered as product. Along the life of an oil-recovery technique it can show how the efficiency evolves.

$$Ex_{RF} = \frac{Ex_{product} - Ex_{fuel} - Ex_{destruction}}{Ex_{product}} \tag{34}$$

Finally, as proposed by Grandell, et al. (2011) and Grassian, et al. (2017), an Exergy Return on investment (EROI) is calculated to examine the quality of an energy source, in this case the oil extracted.

$$EROI = \frac{Ex_{returned\ to\ society}}{Ex_{fuel}} \tag{35}$$

where the *exergy returned to society* is considered as the energy with work potential obtained from the produced oil and gas. This exergy from the produced fossil fuels can be estimated as explained in section 3.3.4 and equation (21). The exergy fuel is estimated as described in section 3.3.5.

In the exergy analysis this ratio can indicate which technique produces the most exergy in relation to the exergy invested as fuel and thus its exergetic efficiency.

As previously mentioned, these ratios can be used to compare different techniques in an efficiency point of view.

3.3.7. Exergoeconomics

As Tsatsaronis (1993) argues, the cost of an energy carrier should be related to its exergy content, as financial resources are invested in a piece of equipment for its hability to perform useful work. Exergoeconomics is the analysis of defining the costs involved with the exergy destruction, the exergy of the product and fuel exergy of a given technique. In contrast with an economic analysis, besides the monetary investments from the capex and opex incurred in the techniques, the exergoeconomic analysis also considers the costs from the exergy destroyed and invested as fuel.

The relation between the associated costs to the exergy components can be expresed in analogy to equation (14):

$$C_{ExP} = C_{ExF} + Z - C_{ExD} \tag{36}$$

where the terms are cost rates per hour ($/hr). Besides the costs related to the exergy fuel and exergy destroyed, the term Z represent the capital expenditures and the operating expenditures, not including the fuel costs, as first defined in the standard NPV analysis from section . This fuel costs have been named Enex in the economic analysis in section 3.3.1. Including operating and capital expenses in the Exergoeconomic analysis allow to stimate the exergy costing of energy carries in relation to their economic investments. The Exergy fuel, coming directly from the energy requirements of the pieces of equipment can be then related to the costing of energy need named in the economic analysis as Enex. If Enex were to be added in the Z factor, a double counting would occur.

If the costs are represented as costs rates per unit of exergy($/kWh), equation (36) becomes:

$$c_P Ex_P = c_F Ex_F + Z - c_D Ex_D \tag{37}$$

where *Ex* represents the exergy units per hour (kWh/hr) that can be obtained directly from the exergy analysis described in the previous section.

Since exergy product, Ex_P, is already calculated in the exergy analysis the incognita then is to estimate the cost rate per unit of product and so from the previous equation we get:

$$c_p = \frac{c_F Ex_F + Z - C_D Ex_D}{Ex_p} \tag{38}$$

The cost rate per unit of exergy of the fuel is estimated by dividing the total Exergy invested in kWh during a certain year by the cost per kWh. This cost is then divided by the number of hours in the given period and a cost per hour ($/hr) rate is obtained. This cost rate is further divided by the exergy rate from the exergy analysis (kWh/hr) to finally obtain the cost rate per unit of Exergy ($/kWh). The cost rate per unit of exergy destruction is calculated following the same steps.

The Z cost rate is estimated by aggregating the Capex and Opex for a given year and then dividing it for the number of hours in the period of time considered.

The product cost per unit of Exergy can then be used as an evaluating parameter between competing alternatives considering exergy efficiencies and their relation to the monetary investment of the technique.

3.3.8. Exergy Considerations for the polymer injection technique

The polymer injection technique is similar to the waterflooding in the way that an injected fluid pushes as a piston additional oil. The purpose of adding polymers to water is to viscosify the injected fluid and as a result to improve the swept of the water front, mobilizing more oil. In this process it will be important to consider the energy needs for the polymer pumping thorough the wells and through the porous media, and the separation of oil from the production stream. As it can be seen in Figure 10, the separation of fluids focuses on separating the oil from the water/polymer mix and then this mix is send for disposal. In contrast with the waterflooding technique, no water or polymers are considered to be reused because in practice it usually turns economically and technically unviable to regenerate the solution to the needed characteristics (Kaminsky, et al., 2007). For the exergy analysis, the disposal of the polymer product means that its chemical exergy is destroyed at the end of the process.

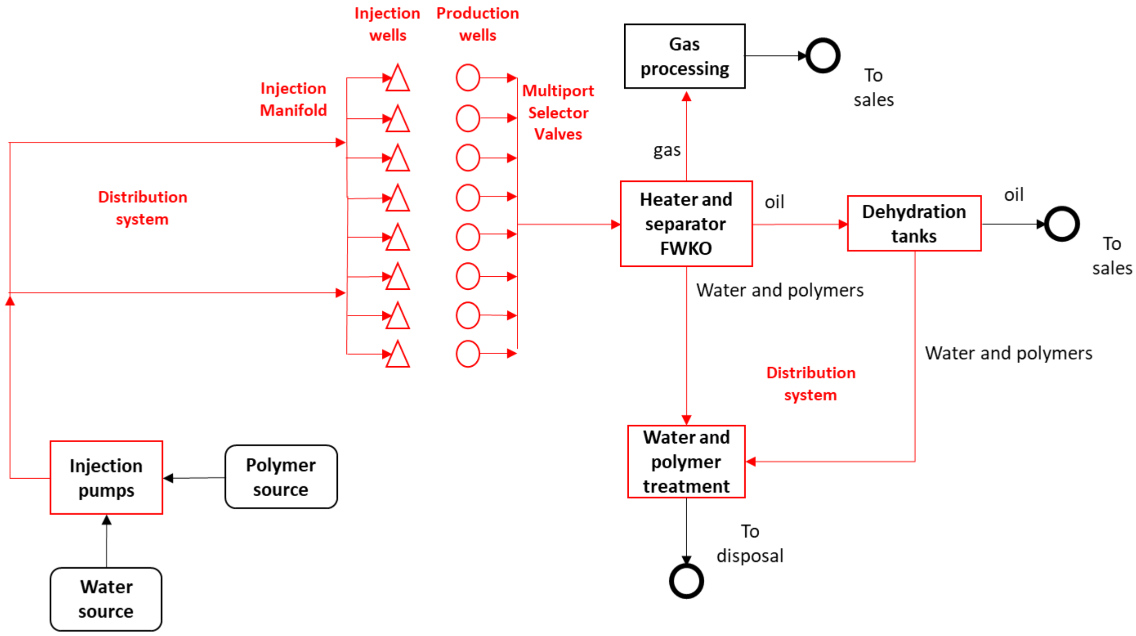

Figure 10. Polymer technique component layout. Red color represents the relevant exergy inputs needed to produce the additional oil.

For the exergy fuel, the same set of equations can be used from section 3.3.5. The same consideration regarding the temperature in the heater is taken as it answers to the characteristics of the oil and gas produced. Given the difference in injected (water and polymer) and produced fluids (more oil produced) the calculations will provide different results for the pieces of equipment considered in Figure 7 and Figure 10.

In the case of the calculations of the Exergy Product it will be needed to consider the additional material in the streams which is the Hydrolyzed polyacrylamide (HPAM) as polymer and calculate its Physical Exergy and Chemical Exergy. For the Physical Exergy equation (20) can be used, but in the case of the Chemical Exergy equation (21) is not appropriate as it relies on known Exergy values per mass of a specific material.

Instead, for the HPAM the chemical exergy is calculated with the following relation (de Swaan Arons & van der Kooi, 2004):

$$ex_{chem\ compound} = gf_{compound} + \sum_{e=1}^{E} N_e \cdot ex_{chem\ element} \qquad (39)$$

where $ex_{chem\ compound}$ is the chemical exergy of a compound in kJ/mol

gf is the Gibs free energy of formation of the compound in kJ/mol

N_e is the number of moles of an element

And $ex_{chem\ element}$ is the chemical exergy of the forming elements of the compound in kJ/mol

Equation (39) provides an exergy unit per each mole of the compound (kJ/mol). For ease of calculations a measure of exergy per mass unit is calculated. In order to calculate the number of moles in a kg of HPAM equation (40) is used.

$$\frac{moles}{mass} = \frac{mass}{compound\ relative\ atomic\ mass} \tag{40}$$

Then, the exergy unit per mass (kJ/kg) for the chemical exergy is obtained by multiplying the exergy unit per mole (kJ/mol) by the number of moles per each kilogram (mol/kg). The Ch Exergy per mass found for the HPAM is 24,712 kJ/kg. The calculations can be found in Appendix L. Since the polymer product is send to disposal after the process is complete, then the chemical exergy from the polymer is considered as destroyed exergy after disposal.

3.3.9. Real Options Valuation

The ability to delay an irreversible investment has the potential to affect the decision to invest at a certain moment. As an analogy, a firm with the capacity to invest holds an option analogous to a financial call option. A firm has the capacity to invest when it considers it to be the most optimum moment. After the firm has exercised this option, and if the investment is irreversible as in many real-life settings, the firm can no longer count with this option in the future. The drawback is, that the firm may lose the opportunity to wait for new information losing the opportunity to wait for possible better market conditions.

In this thesis, the option value is calculated considering uncertainty on the price of oil. In real-life settings many other sources of uncertainty affect the performance of oil recovery processes like geology, technology or present taxes uncertainty to mention some. For this thesis research I focus on the price of oil in order to exemplify the application of real options in waterflooding and polymer injection techniques. For the study of real-life settings more sources of uncertainty are advised to be included.

In contrast with the standard NPV analysis, the scenarios shown in Figure 4 for the estimated oil price by the IEA won´t be used. Instead, two different methods to calculate the Option value will be assed: The solution proposed by Dixit and Pindyck (1994) and the Daatar-Mathews approach (Mathews, 2007). Modelling oil-price behavior is complex since many variables are present in the market. As mentioned in section 3.2, the scenarios proposed by the IEA only consider the effects new energy policies may have on the oil price. The IEA scenarios consider effects on the demand by policy making but do not consider supply or speculative effects. A simulation approach allows to consider more oil price scenarios that could account for the unconsidered uncertainty.

Fernandes et al. (2011) performed a review of Real Option studies applied to energy related projects. Among their review they recognized that the most widely used solution methods were dynamic programming and Montecarlo simulations. In this thesis, both approaches are used in order to illustrate the application of these solutions to oil-extraction techniques.

The solution proposed by Dixit and Pindyck is an analytical approach that follows a dinamyc programming rationale. This approach results of interest because coming out with a set of equations describing the value of an option for the two oil-recovery techniques disscussed in this thesis can illustrate the needed considerations for applying the approach to other oil recovery techniques. The Daatar-Mathews method is a Monte-Carlo simulation approach. This approach takes into consideration as many scenarios as deemed appropriate generating a probability distribution of possible outcomes. This intelligence can be used to account for uncertainties effects and adjust plans accordingly.

3.3.10. Analytical Real Options

Dixit and Pindyck´s analytical approach is based on the consideration that the increment in value of an undeveloped reserve follows a brownian motion process. Similar to a stock call option, the undeveloped reserve has a underlying asset. For the case of the call option the underlying asset is the stock price and in the case of the undeveloped reserve it is the price of a barrel of oil produced (value of developed reserve). Equation (41) shows the increment in value of an undeveloped reserve is equal to a % expected drift in a dt time period (first addend after the equal sign), plus a Brownian motion increment (second addend after the equal sign).

$$dV = (r - \delta)V_0 dt + \sigma V_0 dz \quad (41)$$

where:

V is the value per barrel of oil ($/bbl)

r is the risk adjusted expected rate of return

δ is the payout rate from a unit of produced reserve

σ is the standard deviation of the oil price

dz is the increment in a brownian motion

r is the rate of return a competitive firm would expect from a venture. As in the standard NPV the discount rate is set at 10% following the literature (Harris & Ohlson, 1987; Wei, et al., 2015; Qiu, et al, 2015). In the case of the standard deviation of the oil price σ, Dixit and Pindyck (1994) recommend a value between 15 and 25% based on a study of the behavior of oil prices 30 years prior to the publication of their book. Since in recent years the prices of oil have evolve dramatically, it was deemed necessary to obtain an updated standard deviaton. The oil price history from May 1988 to April 2018 (The World Bank, 2018) was analyzed in Appendix I, obtaining a standard deviation of 30%.

The parameter δ is very important for differantiating between oil-recovery techniques, as it includes in its calculation a *w* oil production decline rate, unique to each technique; the % value of one barrel of oil and the % profit per barrel of oil which will also be different for each technique. The difference in this analysis between value and profit from a barrel of oil, is that the value takes into account all associated costs including initial investments, while the profit per barrel only considers marginal costs, thus $\pi > V$. The values of π and V were obtained from the standard NPV analysis for each technique considering Capex and Opex and only Opex respectively with respect to the revenues. This values were obtained from the NPV analysis as it will also vary depending on the studied technique. Similarly to the payout rate δ, Dixit and Pindyck recommend a V of .33% and a π of 46%. The values calculated for this thesis differ from those proposed by dixit and Pindyck and are shown in Table 7 below.

For the *w* production decline, an average production rate was obtained during the producing life of each technique. Equation (42) shows the calculation of δ.

$$\delta = w\frac{\pi - V}{V} \tag{42}$$

Table 7 shows the parameters used for the calculation of δ and results for each technique:

Table 7. Parameters calculated for the Wiener Process for the oil-recovery techniques.

Parameter	Waterflooding	Polymer flooding
w	5%	7%
V%	47%	47%
π	52%	57%
δ	0.5%	1.5%

In order to asses the opportunity cost of the option, the contingent claims method (Dixit & Pindyck, 1994) is used to define the partial diferential equation that relates the option value (*F(V)*) to the value of the developed reserve.

$$\frac{1}{2}\sigma^2 V^2 F''(V) + (r-\delta)VF'(V) - rF(V) = F(t) \tag{43}$$

Equation (43) cannot be solved analytically but it is possible to obtain numerically a solution through finite difference methods. The term *F(t)* is a representation of a reliquinshment requirement or in other words, the option to develop the reserve is not perpetual and must be exercised within a time constraint. As analyzed by Dixit and Pindyck (1994) the effect of such time constraint is negligible for periods greater than two years. If the F(t) is assummed to be zero then we get:

$$\frac{1}{2}\sigma^2 V^2 F''(V) + (r-\delta)VF'(V) - rF(V) = 0 \quad (44)$$

In this case the equation above can be solved analytically obtaining the next set of equations:

$$F(V) = AV^{\beta} \quad (45)$$

where *F(V)* is the value of the undeveloped reserve while *A* and *β* are constants that are calculated.

$$\beta = \frac{1}{2} - \frac{r_f - \delta}{\sigma^2} + \sqrt{\left[\frac{r_f - \delta}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r_f}{\sigma^2}} \quad (46)$$

β is a quadratic root of a second order homogeneous differential equation obtained from the payout rate from a barrel of produced reserve *δ*, the risk-free interest rate r_f and the standard deviation of the value of a developed reserve σ. The risk free interest rate r_f is obtained from the U.S. department of Treasury (2018) for Treasury bills.

The constant *A* is given by:

$$A = \frac{V^* - I}{(V^*)^{\beta}} \quad (47)$$

where *V** is the optimal value at which the company should invest immediately, that is, when the Value of the developed reserve minus the opportunity cost is at least equal to the investment.

$$V^* = \frac{\beta_1}{\beta_1 - 1} I \quad (48)$$

Considering equations (45) to (48), it is now possible to estimate the returns of exercising the option at a given time. These return will have two components: the flow of profits from production in the immediate year and the value of the undeveloped reserve F(V) (Dixit & Pindyck, 1994).

$$Return = V(w \times B) + (F(V) \times B) \quad (49)$$

where

w is the oil production decline per year

B is the total produceble oil

The return calculated is considered as the option value and can then be compared with other oil recovery techniques or with the option to wait for information and exercise the option in a consecutive year.

3.3.11. Iterative Real Options

In the case of the Daatar-Mathews method, a different approach is followed. With the use of equation (50) a simulation of the oil price is performed. The oil price behavior in the future is uncertain as it is tied with technological, social, political and market pushes and pulls. A Wiener process can be used to capture the behaviour of a variable which value is independent of past performance and which presents a stochastic behavior. Similar to stock prices, the oil price cannot be considered to be normally distributed but its increments or decrements can be assumed to (Zakamulin, 2016). This increments then are modelled as a Brownian motion.

$$dP = \mu_p P dt + \sigma_p P dz \tag{50}$$

where μ_P is the expected rate of change in a given time period and is simmilarly calculated in Appendix I with the data from the World Bank (2018).

In order to account for the distribution of possible scenarios, the oil price behavior is modelled several times. In this thesis research, one thousand iterations are performed each with a different oil-price behavior that follows a random walk path. The number of iterations chosen follows the recommendations found in the literature (Mathews, 2007; Guedes et al., 2016).

Next, for each oil price scenario a NPV is calculated. For every oil price scenario the gross revenues and net profits will be calculated as explained in the standard NPV analysis including the considerations for the polymer technique in section 3.3.1and 3.3.2.

This “strategic intelligence” as Mathews (2007) names it, is then analyzed and the net profits for all possible scenarios collectively determine the real option value of the technique. The mean is then obtained from the NPV distribution. This value is considered as the option value. Equation *(51)* illustrates this notion:

$$RO\ value = \frac{\sum_{e=1}^{E} NPV_e}{E} \tag{51}$$

where *e* is an specific iteration and *E* is the total number of iterations. The advantage of this method is to be able to consider many possible scenarios, up to thousands, and get a more complete picture of the possible outcomes. Considering optimistic high oil prices but also conservative low prices. In contrast with the standard NPV method where only three defined scenarios of oil price by the IEA are considered. Every possible scenario in-between or beyond are not taken into account in the standard NPV analysis. Besides, the IEA scenarios consider possible policies developments and do not consider important market forces like supply and demand. It is for this reason that an iterative approach is useful to capture uncertainty that has not been considered.

3.4. Comparison of the results

After obtaining all the data and conducting the discussed analyses, the results will be compared. The differences between the economic, real options and exergy evaluation will also be studied. Finally, cross-case evaluation will support the robustness of the research and will allow to draw recommendations on the applicability for considering efficiencies and uncertainty in the evaluation for oil-recovery projects.

In order to compare the results from different criteria, a best technique will be selected for each assessment. In the case of the economic appraisal the one with the highest NPV will be selected. In the case of the exergy analysis the technique with the best Exergy ratios will be selected as the recommended technique. Finally, for the appraisal of real options, the technique or option with the highest uncertainty adjusted NPV, called option value, will be selected.

To make this comparison only the performance after year 3 will be considered for both techniques. Since for the polymer injection the first 2 years only water is injected, the performance of both techniques is identical in this period of time. For this reason, the waterflooding will be considered as a base case and the NPV, exergy and real-option value increments as a result of polymer injection will be used for the comparison.

After making the comparison analyses the results will allow to distinguish the advantages and disadvantages of including real options and exergy in the evaluation process.

4. Waterflooding Technique

4.1. Economic appraisal

Following the methodology described in section 3.3, the NPV is calculated for the waterflooding technique. The base costs and the estimated costs for this thesis can be found in Appendix B. From the cost estimates provided, the scaled down costs for a small project of eight injectors and eight producer wells are calculated using equation (6). The value of $Cost_1$ will be the original cost of the big scale operation, the value of $Size_2$ and $Size_1$ are not the number of wells, but in this case the capacity per unit (m^3/d) of each equipment. The scale factor used for these estimates is 0.6 as provided by the external advisor. The equipment capacity per unit is calculated in Appendix A and responds to the volumes of injected and produced fluids. For the injector and producing wells 700 m of depth is considered as seen in Table 1. Table 8 shows the scaled down estimated Capex per equipment/upgrade needed.

Table 8. Case study scale waterflooding capital expenditure estimates.

Gross needed injected flow rate	640 m3/d
Water cut	0.9
Water injection	Assumes all PW is reinjected
Number of producers	8
Number of injectors	8
Flow per injector	80 m3/d
Gross per producer	80 m3/d

Box	Item	Number	Capacity per unit (m3/d)	Total Cost (million $)
Separation of produced fluids	FWKO	1	640	0.02
Separation of produced fluids	Booster Pumps	2	76.8	0.28
Separation of produced fluids	Export pumps	2	64	0.32
Separation of produced fluids	Heaters	1	76.8	0.37
Separation of produced fluids	Dehydration Tanks	2	76.8	0.004
Water treatment Plant	Nutshell Filter	1	576	0.19
Water treatment Plant	Backwash System	1	576	0.20
Water treatment Plant	Tanks	1	576	0.12
Water injection	Pumps	1	3600	1.81
Water injection	Manifolds	1		0.40
Water injection	Distribution system	8		2.40
Production Gathering	MSVs	2		0.80
Production Gathering	Distribution system	8		4.00
Producer well cost		8		12.00
Injector well cost		8		8.00
Total Capex				**30.93**

Having calculated the Capex, the operating expenses for this technique are estimated. In the literature (Hard & Deren, 1991; Westney, 1997; Macary, et al., 2000), different approaches can be found in relation to Opex estimation. One of the approaches consider a % of Capex per year, with a value of 10% common in the case of secondary oil-recovery techniques. Another approach is to consider an average cost per barrel of oil and per barrel of water produced (Macary, et al., 2000; Jaber, et al., 2017). For this thesis it was prefered the cost per barrel stimation approach in order to account for the changes in production profiles along the years. The Opex can be found in Table 5.

Using the estimated additional oil produced as a result of applying the waterflooding technique (Appendix A), and the injected volumes of water, it is possible to estimate the Opex per year basis. The full Opex calculations can be found in Appendix B. Besides the calculated Opex the cost of energy used is estimated independently in order to estimate the fuel exergy cost and can be found in section 4.3.

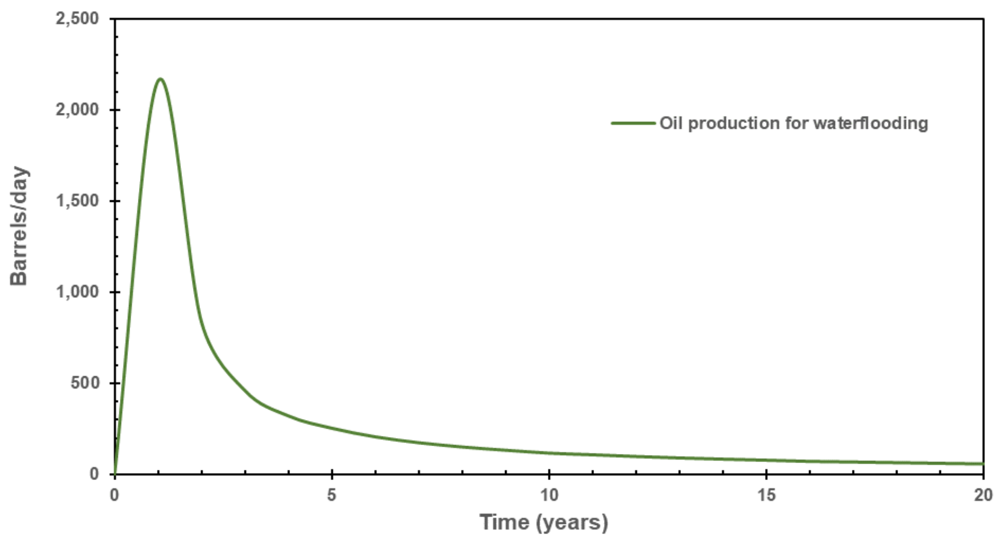

Figure 11. Oil production as a result of the waterflooding technique.

Figure 11 shows the additional oil produced once the technique is applied. A sharp increase of oil followed by a decline in production can be observed. This behavior results from the piston-like effect the injected water has, forming an oil bank and then when water reaches the producing wells, oil production declines and water production increases. In order to estimate the revenues, the simulated amount of extra oil produced is multiplied by the forecasted oil price in the subsequent years. In real life settings some firms may prefer to shut down operations once oil production reaches a certain oil production threshold, in other applications oil would be produced as long as it is economically feasible some spanning more than 30 years (Beliveau, 2009). In this thesis it is assumed that oil production continues as long as it is economically feasible. In real-life settings this assumption would respond to firm strategic decisions.

In this thesis a sensitivity analysis is performed on the oil-price effect on the economic performance of the technique. Three different oil price behaviors will be considered based on the projections by the IEA shown in Figure 4 and three different discount rates. Table 3 summarizes the conditions considered for the sensitivity analysis.

Having calculated the Capex, Opex and revenues it is possible to estimate the cashflows per year and ultimately the NPV for this set of conditions. Appendix B presents the estimations considering three different discount rates and the three IEA oil price scenarios. Table 9 shows the NPV for the IEA second scenario "New Energy policies" and the discount rate of 10% found in the literature as common in oil recovery projects (Harris & Ohlson, 1987; Wei, et al., 2015; Qiu, et al, 2015).

Table 9. Cashflows for the waterflooding technique considering oil price scenario 2 and 10% discount rate.

Year	Discounted Revenue ($ dollars)	Total costs discounted ($ dollars)	Cashflows ($ dollars)
0	$ -	$30,932,906	$ (30,932,907)
1	$40,105,408	$3,549,760	$36,638,529
2	$15,120,938	$2,205,358	$12,999,692
3	$8,081,550	$1,727,234	$6,433,790
4	$5,455,717	$1,458,509	$4,070,622
5	$4,152,295	$1,300,437	$2,918,978
6	$3,248,678	$1,155,481	$2,154,548
7	$2,628,464	$1,033,646	$1,650,816
8	$2,176,471	$928,442	$1,299,098
9	$1,796,895	$836,140	$1,007,305
10	$1,480,116	$743,536	$779,079
11	$1,273,312	$681,531	$630,419
12	$1,085,717	$616,259	$504,649
13	$932,254	$557,654	$406,647
14	$801,787	$504,917	$326,049
15	$693,024	$457,379	$262,210
16	$591,991	$408,503	$207,718
17	$524,623	$375,715	$170,922
18	$458,560	$340,659	$137,940
19	$401,204	$308,942	$110,501
20	$351,967	$280,232	$88,336
		NPV	**$40,957,732**

When comparing the two different techniques this NPV will be used.

4.2. Economic sensitivity results

In this section the insights obtained from the sensitivity analysis will be discussed. First, the contribution to the total Opex was analyzed for each of its components, the oil handling costs, water handling costs and energy costs. Figure 12, in absolute costs, and Figure 13, in contributor percentage of total costs, show how initially the oil handling were the main contributor to the Opex. The costs associated with oil production quickly decrease as production declines due to the water breakthrough occurring in the first years of the technique.

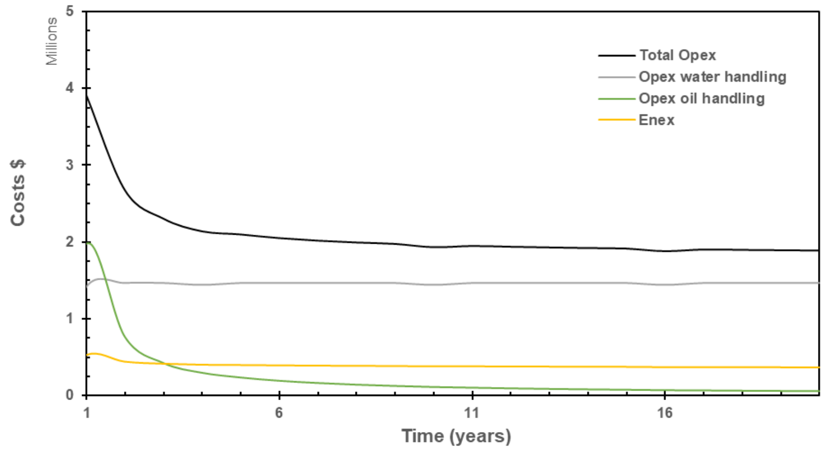

Figure 12. Total Opex and Opex components along the waterflooding technique life.

Since the injection flow-rate of water remains constant along the years so will the opex derived from the handling of water. For the energy expenditures it can be seen a slight increase at the beginning due to the increased oil production, which in turn requires higher energy expenditures to process the volumes of oil.

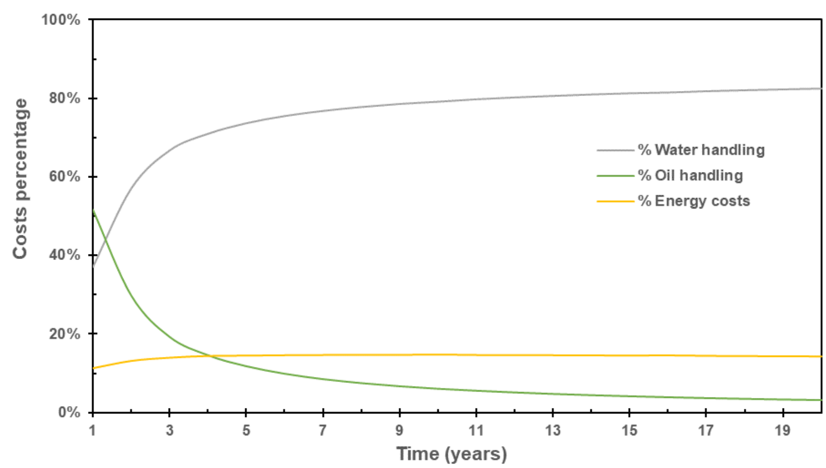

Figure 13. Percentage of Opex components to total Opex.

Figure 13 illustrates that at the beginning of the water injection the contribution of oil handling is up to 52% of the Operating expenditure while at year 20 it is only 3% of total Opex. In the case of water handling expenditures, it increases from 37% up to 78% as the fractional production becomes more water and less oil. In the case of the energy expenditures it remains rather constant accruing to 13% of operating expenditures. The reason for the Enex to remain almost constant results from the notion that most of the energy requirements, as seen in Appendix D and discussed in section 4.3, comes from the pumping and treatment of water.

When considering the Capex shown in Table 8, three main contributors to the expenditures can be recognized: The Capex from the wells, the pumps and the rest of the Capex. In order to observe the effect of a cost increase in the final NPV, each Capex and Opex component was increased by 10%. Figure 14 shows the % change to the NPV if one of the estimated costs were to be higher, this analysis is relevant as in practice cost estimations can be off from real prices.

In order of importance, the Capex of the wells and the Opex of water-handling are the components with the biggest impact with a NPV decrease of 4.4 and 2.7%, respectively. The importance of this insight is that if estimations are off, and costs result higher than expected, these two components would affect the economics of the technique the most. On the other one hand, efforts could be aimed at decreasing costs in these two components as it would yield the best results to the overall economics.

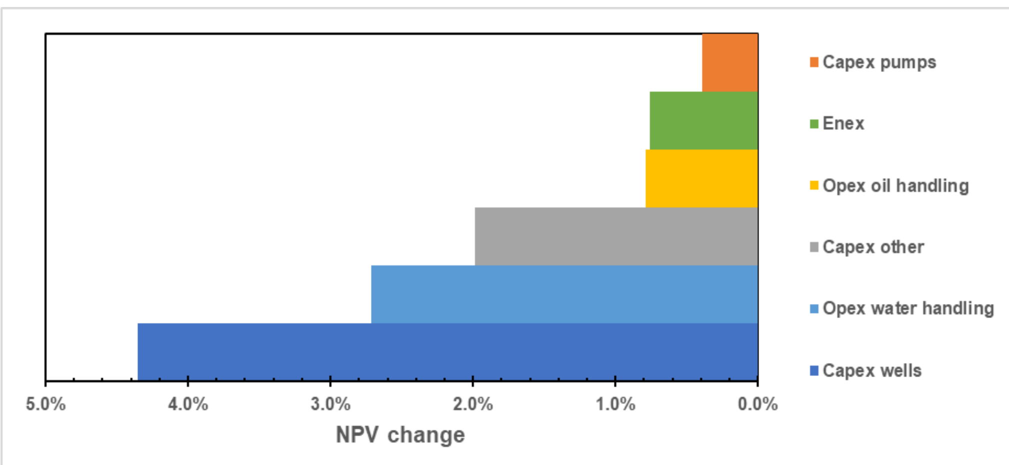

Figure 14. % Change in NPV as a result of 10% increase in an expenditure component for the waterflooding technique.

In order to analyze the effect of a change in discount rate, three values were selected: 10%, as seen in the literature (Harris & Ohlson, 1987; Wei, et al., 2015; Qiu, et al, 2015), 5 percentile points above and 5 percentile points below this value to assess the effect in the project economics.

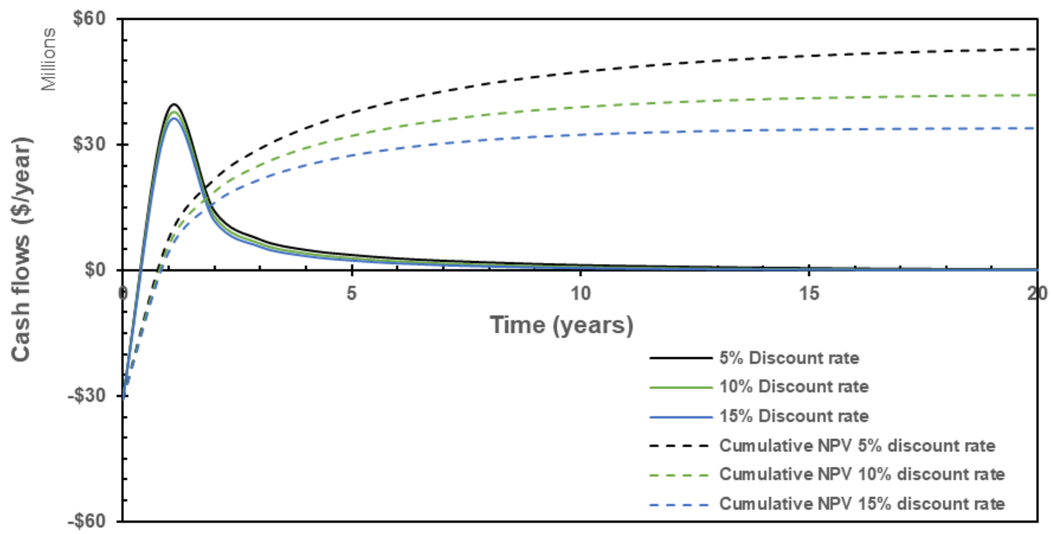

Figure 15. Yearly cashflows and cumulative present value for 5, 10 and 15% discount rates for the waterflooding technique.

Figure 15 shows the cashflows per year and the cumulative present value of the different cases where discount rates are varied. Because of the long life of the technique, the effect of a variation in discount rate is important. Between the 10% and the 5% discount rate, the NPV varies as much as 26%. In the case between the 15% discount rate and the 10% discount rate the NPV varies up to 19%.

If the cashflows per year are divided by the additional oil production in that particular year, it is possible to visualize the profitability of the project in a year in relation to the previous ones. As the oil production declines so does the dollars gained per barrel of oil produced. Figure 16 shows that, if an economic limit is preferred by the firm ($profit/barrel), then the project becomes uneconomic at different moments in time depending on the discount rate. Having a heavier burden on the economics, a discount rate of 15% would become uneconomic sooner than with a discount rate of 10% for example. The economic limit presented in Figure 16 is only an example for visualization and as mentioned earlier, in this thesis the NPV considers all positive cashflow.

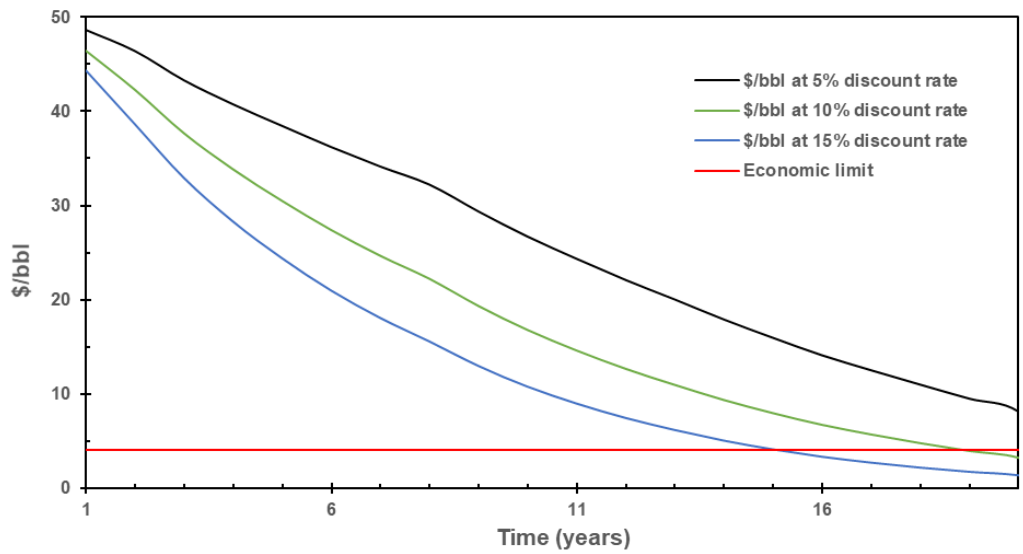

Figure 16. Profit per barrel of oil produced considering 5, 10 and 15% discount rates.

Next, the sensitivity analysis for the IEA oil price scenarios with a constant 10% discount rate is performed. Figure 17 shows the cashflows per year and its cumulative per each oil price behavior scenario. In comparison to the last sensitivity analysis, at the beginning of the techniques there is less variation between cases. This behavior results from the similarity in oil price scenarios in the years close to the present. Since uncertainty increases over the years, the biggest difference on predicted oil price between scenarios are shown at the later years. Considering that oil production rate is bigger at the beginning for this technique, the cashflow behavior is then similar for the three scenarios at the beginning.

However, the production tail after the water breakthrough causes the cumulative present value to differ per scenario. In the case of scenario 1 and scenario 2 a difference of 12% is observed in the final NPV. Between the scenario 2 and scenario 3 similarly a 12% difference is observed.

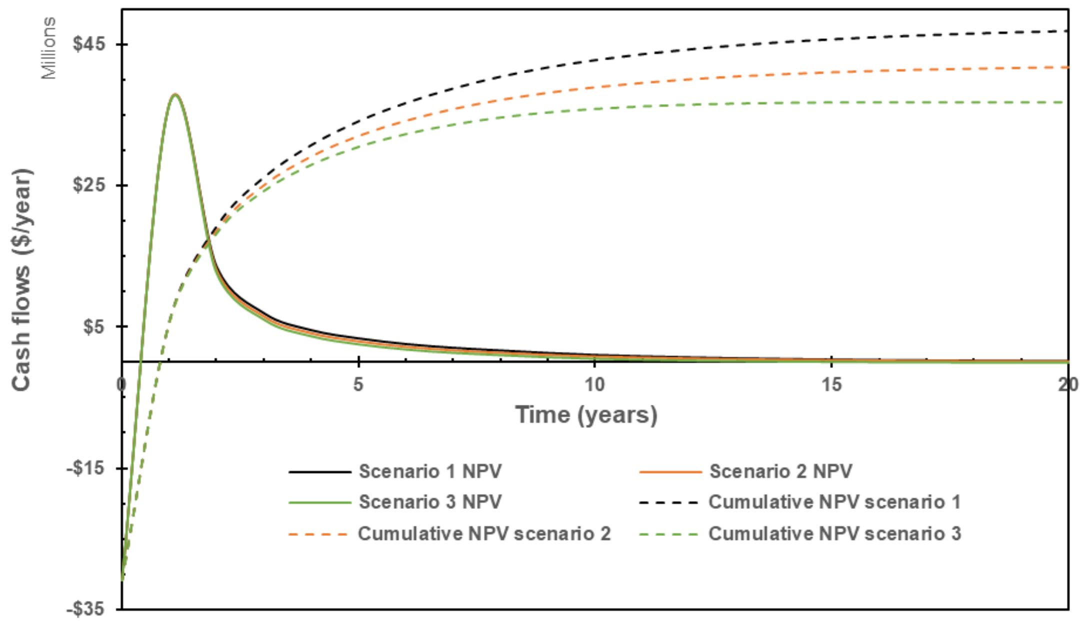

Figure 17. Yearly cashflows and cumulative present value for 3 oil price behaviors following IEA scenarios for the waterflooding technique.

The oil price impact is more evident in Figure 18. In this graph it is shown that a scenario 3 or that of “sustainable development” would make the technique uneconomic by year 16 even without considering an economic threshold and earlier if one is indeed considered. Scenario 1 presents a more optimistic oil price development which is reflected in higher $profit/barrel produced in comparison with Scenario 2 and scenario 3. In sum, as sustainable energy policies are set in place, the more likely that the profitability of oil recovery projects decrease.

In order to summarize the sensitivity analyzes from Appendix B, Figure 19 shows the NPV for the three different oil price scenarios and each with three different discount rates. Using this graph, it can be seen how the NPV varies for the same discount rate through different oil price scenarios and the effect of different discount rates.

This economic analysis can be used to analyze the performance of the techniques, in a standalone fashion and aim for improvements. The results can also be used to obtain a preferred technique from the alternatives.

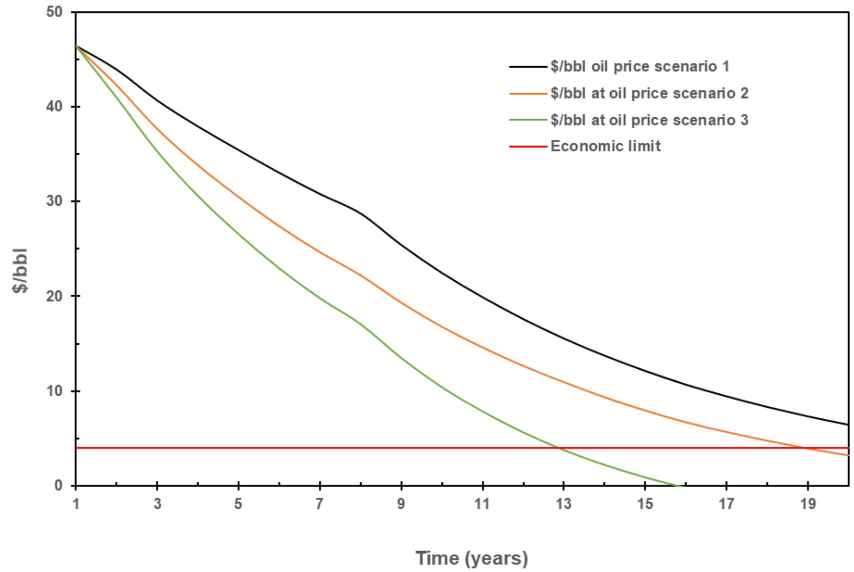

Figure 18. Profit per barrel of oil produced considering three different oil price scenarios by the IEA for the waterflooding technique.

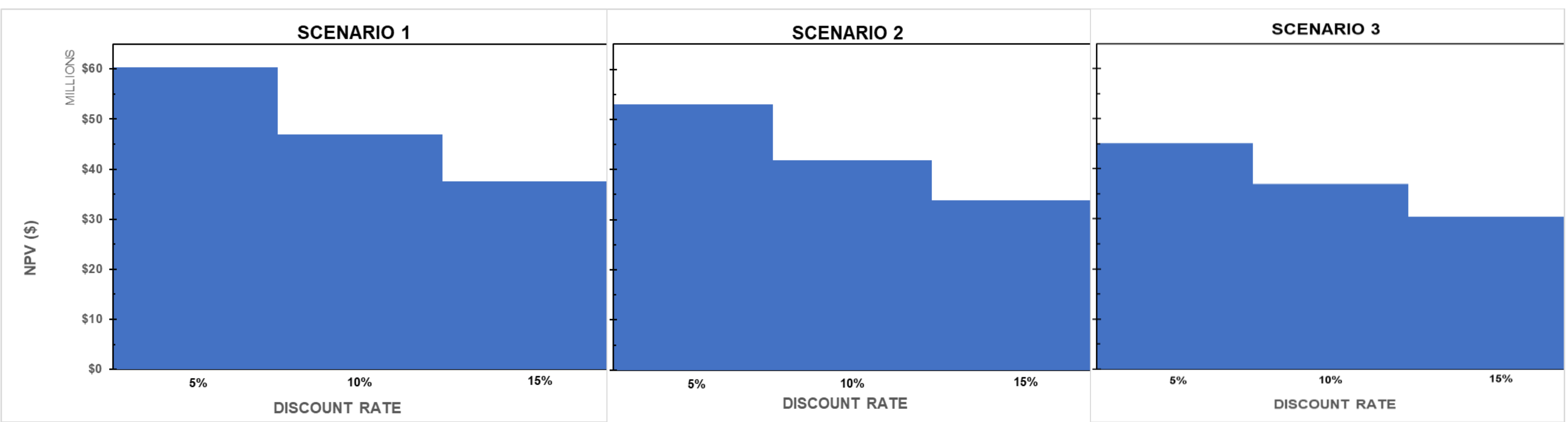

Figure 19. Sensitivity analyses summary for discount rates and oil price behaviors for the waterflooding technique.

4.3. Exergy analysis

Having described the waterflooding technique in Figure 7, an exergy analysis is performed by describing its exergy inputs and outputs. In this thesis, Exergy is considered as the energy fraction that is used to perform useful work. The energy fraction that is dissipated without performing work as a result of irreversivilities (e.g. pump and drive inefficiencies) or waste flows (e.g. temperature transmission) is known as exergy destruction (Stougie, 2014).

Following the methodology described in section 3.3.3, the first step is to calculate the exergy in the material streams that goes in the energy carriers and that which goes out. This exergy is known as product Exergy and allows to visualize what happens to the material streams due to the exergy investment in the equipment units.

Appendix C shows the Product Exergy calculations were the Exergy content of each stream is considered. In other words, for every energy carrier (Injection pump, heater, coalescer and water treatment) a stream-in and a stream-out is analyzed in relation to their Exergy content. Appendix D presents the calculations for the Exergy Fuel and Table 10 summarizes the results obtained for the Product and Fuel Exergy.

Table 10. Exergy product, Exergy fuel and exergy destroyed summary for waterflooding

Components	Pump A.1	Pump A.2	Pump A.3	Pump Atot	Heater and separator	Dehydration	Water treatment	Total
Ph Exergy i (W)	166,928	39,185,209	-364,969		59,851	-57,135	0	
Ch Exergy i (W)	0	38,939,357	0		0	0	0	
Total Product Exergy	166,928	78,124,566	-364,969	77,926,525	59,851	-57,135	0	77,929,240
Exergy Fk (W)	0	0	0	230,612	175,991	2.6654	128,010	534,615
Exergy Dk (W)	0	0	364,969	364,969	116,140	57,138	128,010	666,257
yD				**55%**	**17%**	**9%**	**19%**	

As discussed in section 3.3.6, the yD ratio is the relation between the exergy destroyed in one equipment in comparison to the total exergy destroyed in the technique. Figure 20 shows visually how the exergy destruction is distributed in the equipment units.

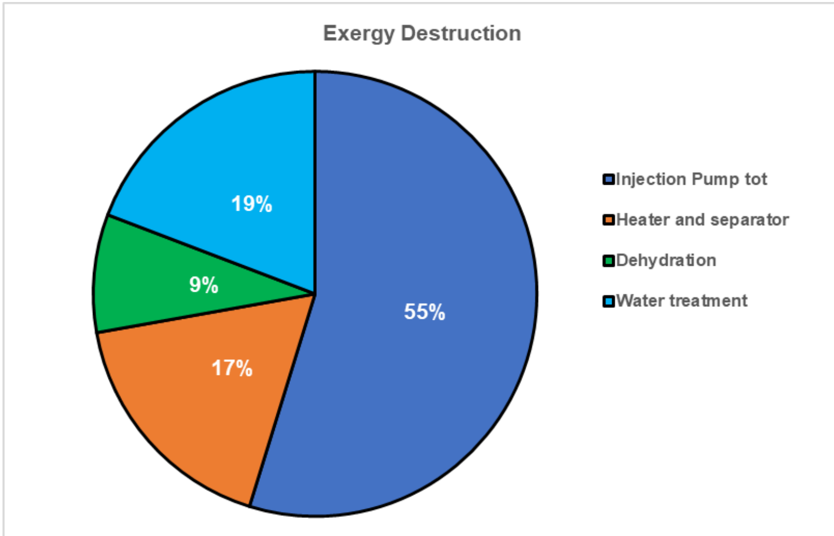

Figure 20. Exergy destruction contribution per energy carrier for the waterflooding technique.

The major contributor to exergy destruction lies in the injection pumps, as pushing the fluids is energy intensive. This study points to the importance of using efficient injection pumps and drivers. The next contributor in exergy destruction is the water treatment, mainly due to the fuel exergy needed as a result of the water volumes treated.

The fuel exergy will be greatly influenced by the amount of fluids pumped and produced. Since the injection of water remains rather constant along the years and the production volumetrically speaking varies slightly (less oil every year), the exergy invested to keep the technique going remains almost constant as seen in Figure 21. In the case of the Exergy destruction, it will be mostly influenced by the wasted energy by heat transmission and depressurization in the oil phase due to its higher specific enthalpy and entropy relative to water and gas.

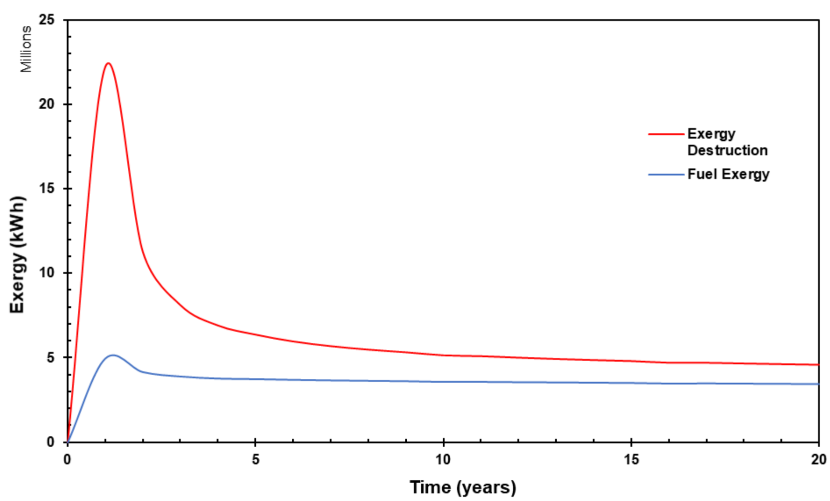

Figure 21. Fuel Exergy and Exergy Destruction for Waterflooding

Figure 22 shows the product exergy behavior along the years. It is considered important to point that the product exergy includes the physical and chemical exergy. Since oil presents a higher specific chemical exergy, entropy and enthalpy in relation to water and gas, so will the product exergy be influenced more in relation to the amount of oil produced. In this Figure it is possible to observe how product exergy is greater in the first couple of years just as oil production is greater in the same period and quickly decreases as oil production declines.

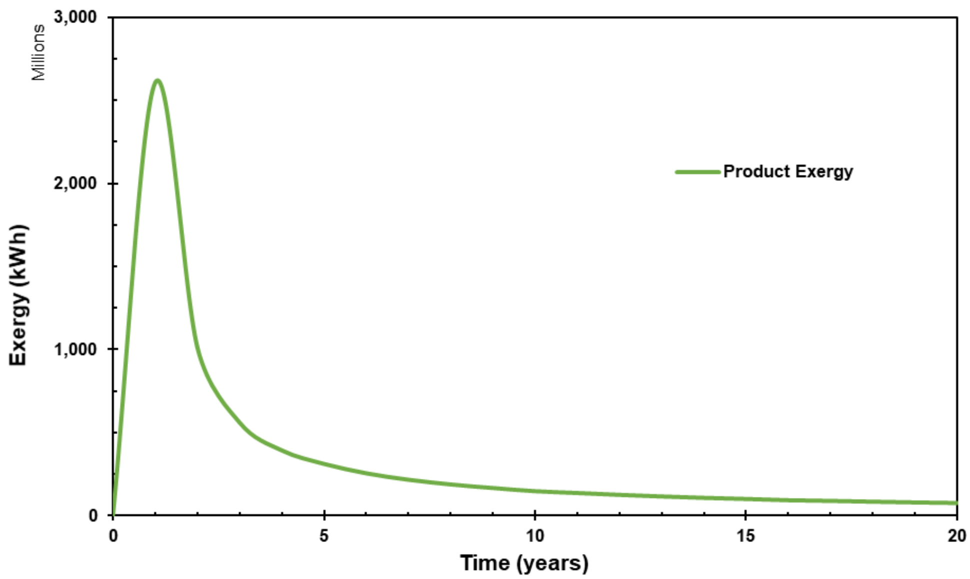

Figure 22. Product Exergy for Waterflooding.

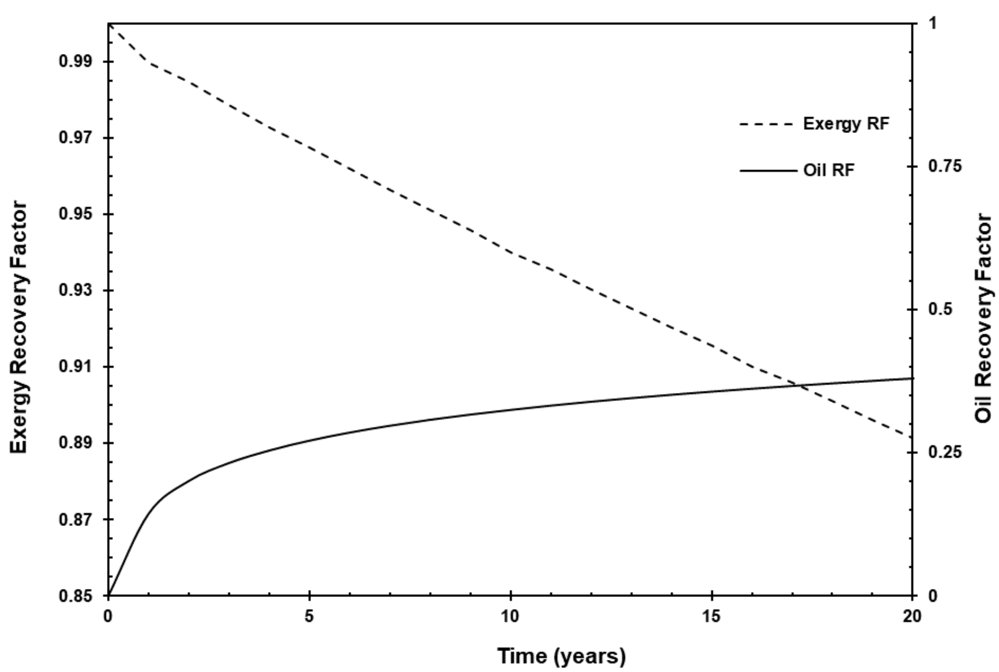

Figure 23. Exergy Recovery Factor for Waterflooding.

By using equation (34) it is possible to calculate the exergy recovery factor. The exergy recovery factor represents how much exergy is being obtained as product in comparison with the invested and destroyed exergy. As years go by, the exergy RF decreases hinting that the process becomes more inefficient as less Exergy Product is obtained in relation to its investment and destruction. On the other hand, the oil RF refers to how much oil is recovered in comparison with the oil originally in place. Figure 23 shows how the Oil RF increases to a maximum of 38% after 20 years of oil production and the exergy recovery factor declines to 89% by that same period.

Considering an almost constant fuel exergy, it can be observed in Figure 24 that as oil production declines, the needed invested kWh per barrel produced increase.

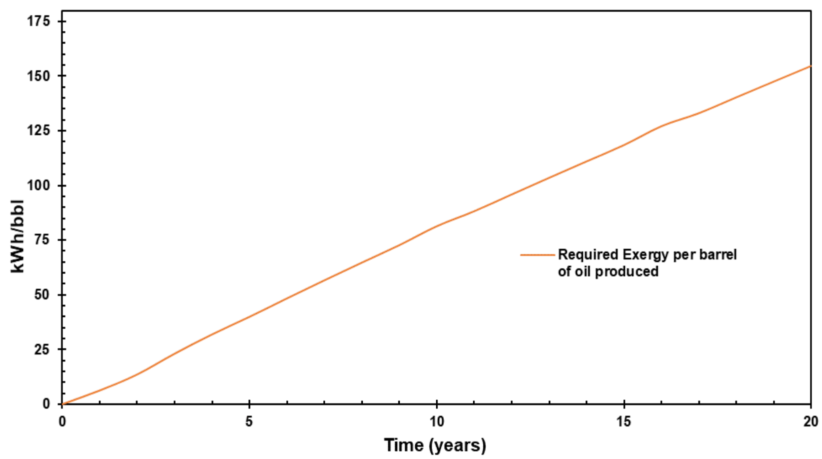

Figure 24. Required Fuel Exergy per barrel of oil produced for the waterflooding technique.

Figure 25 shows how the cumulative net exergy, the subtraction of the product exergy minus the fuel or invested exergy, has a similar behavior to that of the cumulative cash flows. The incremental revenues and incremental Exergy recovered decrease in the late years to a point where they get close to constant, as this occurs, the profitability of the project decreases and so does its exergetic efficiency.

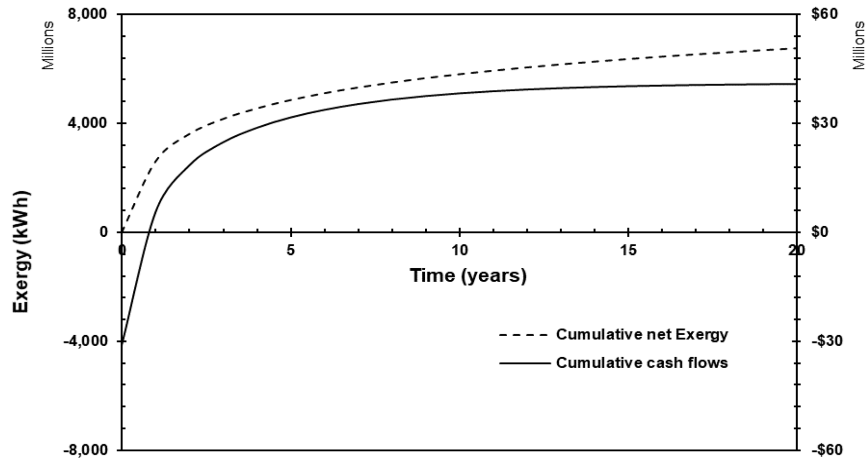

Figure 25. Cumulative net Exergy and cash flows for the waterflooding technique.

An exergoeconomic analysis allows to stablish the cost per exergy unit not only in consideration to the cost of fuel but also the operating expenses of the technique and the capital cost of the energy carriers. The rationality behind including the Capex on Exergy costing is that such investments are made with the objective of obtaining useful work with such equipment units. Equation (36) and (37) show the relation between the cost of the product exergy, fuel exergy, capex, opex and exergy destruction.

As Figure 26 shows, the cost rate of the product exergy is much larger than that of the fuel exergy and the exergy destruction. The reason the cost rate for the exergy product declines in year one results from considering the Capex at year zero as part of factor Z, which takes the cost rate of the Product Exergy to be up to $3500 per hour. Then, in contrast, from year two onwards, the hourly cost of the Product Exergy is $180 where only opex is considered in the factor Z.

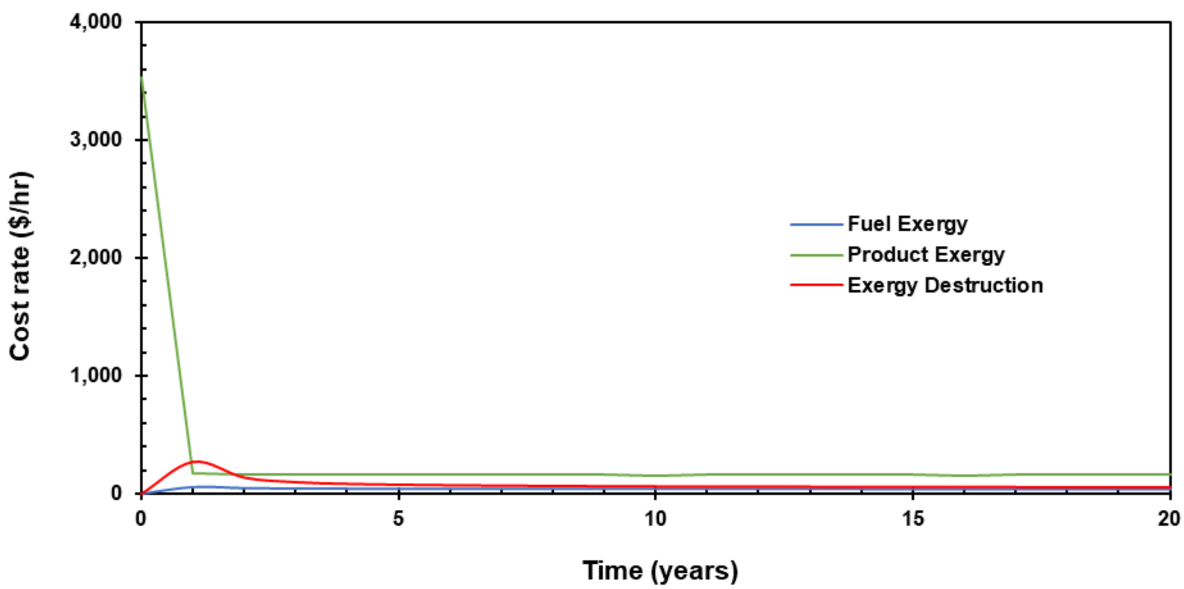

Figure 26. Cost rate of Product, Fuel and Destroyed Exergy for waterflooding.

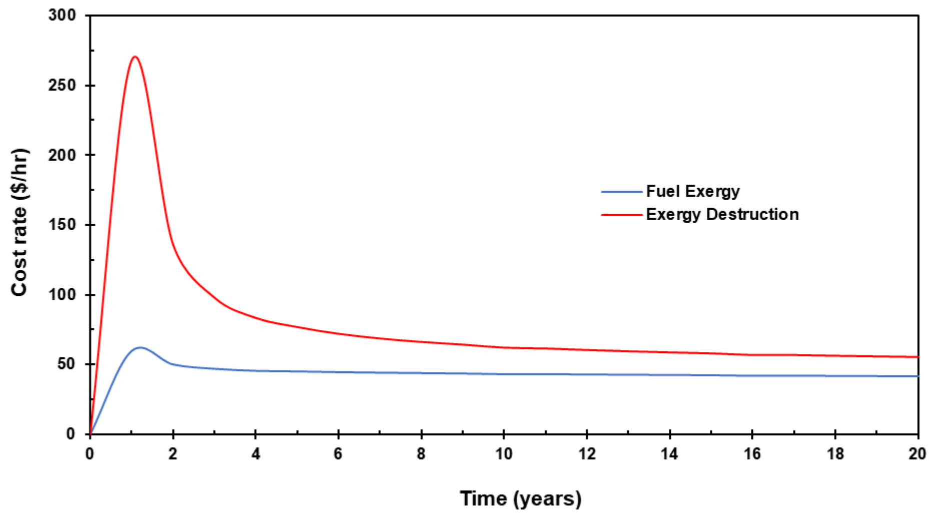

Figure 27. Cost rate of Fuel and Destroyed Exergy for waterflooding.

Figure 27 shows also the cost rate but now with focus on the fuel exergy and exergy destruction. The fuel exergy remains mostly constant along the years as it considers a constant price per kWh of invested exergy, as shown in Table 5 (European Union Statistical Office, 2018). The exergy destruction varies mostly at the beginning of the technique because more exergy is destroyed every hour in the first two years which as a result increases the cost per hour incurred due to exergy destruction.

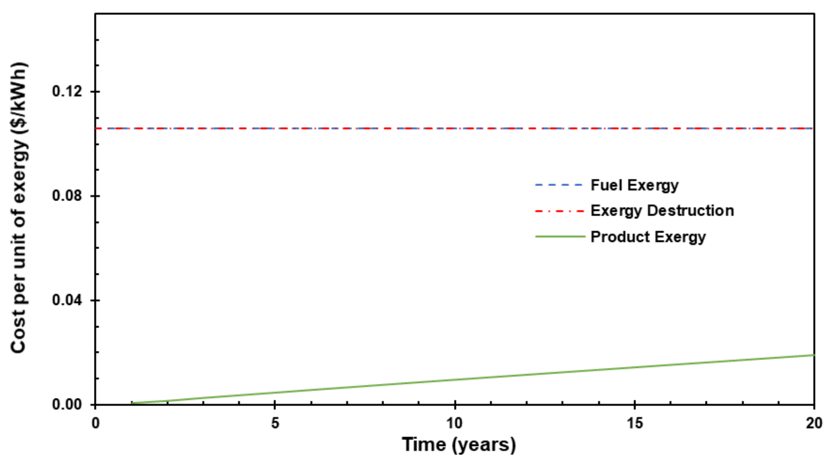

Figure 28. Cost per unit of Exergy for Fuel, Product and Destroyed Exergy for waterflooding.

Let us analyze the behavior of the needed investment to recover product exergy or the cost per unit of Exergy. As it can be seen in Figure 28 the cost per kWh recovered increases over the years due to declining efficiency. The destroyed exergy is costed the same since the fuel exergy as it is considered as an extra fuel needed to be supplied, in order to generate the same exergy flow rate accounting for the destroyed exergy (Tsatsaronis G. , 1993).

The Exergy parameters described can as well be used to compare competing techniques in relation to their efficiency performance.

4.4. Real option value

In order to account for uncertainty in the evaluation of the profitability of the waterflooding technique, a Real Options analysis is performed. The parameter considered for uncertainty is the oil price along 20 years in the future. As described in section 3.3.9 the Real option value of exercising the investment decision of Waterflooding is analyzed following two different approaches: The Dixit and Pindyck analytic approach (1994) and the Daatar-Mathews Monte Carlo simulation approach (Mathews, 2007).

The main focus of the analytic approach is to define the option value to invest at a given year. Following equations (41) to (49), the opportunity cost, optimal investment value and the value of the option are calculated.

Table 11 summarizes the results for the analytical RO analysis and, for brevity, presents them for years one, five, ten and twenty only. The complete analysis can be found in Appendix F.

Table 11. Analytic RO results summary.

Year	P ($/bbl)	V ($/bbl)	V* ($/bbl)	F(V) ($/bbl)	Option value undiscounted ($ millions)	Option value discounted ($ millions)
1	56	27	221	21	65	65
5	77	36		30	90	61
10	118	56		47	141	60
20	181	86		75	222	36

Table 11 shows a distinction between the price of oil *P* and the Value of a barrel of reserve *V*. This distinction is present along the set of equations to distinguish the market price of a barrel of oil and the real value after costs per each barrel. Dixit and Pindyck (1994) based on literature review assume that the real value of a barrel of oil is around a third of its market price. In this research, having information on operating and capital expenses, this value was calculated instead. For the waterflooding oil-recovery technique it was found to be 0.47, while Dixit and Pindyck (1994) assumes 0.33.

The *V** value or the optimal value of a barrel of oil is such that the firm should invest right away without any advantage to wait for any further information. Figure 29 show the optimal value *V** with the evolution of the value of a barrel of oil according to a Brownian motion process (Durrett, 2000).

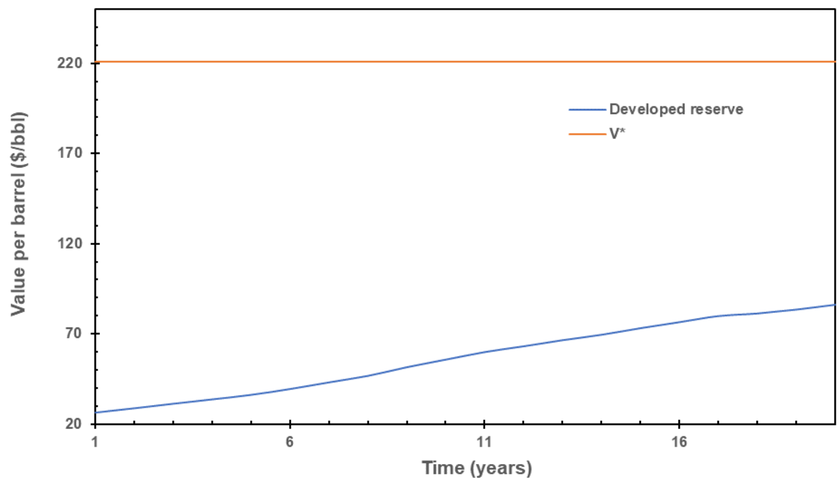

Figure 29. Optimal investment value and developed reserve value for the Waterflooding technique.

The picture above shows that, if the oil price follows the described random walk, it would not reach the optimal value V* even if the firm were to wait 20 years for new information. This doesn´t mean the firm should never invest as will be explained next.

As can be seen in Figure 30, the value of exercising the option at a given year increases with the time horizon. This results from the notion that, according to equation (45), if the value V of a barrel of oil increase, so does the opportunity cost of exercising now and not waiting for a higher price.

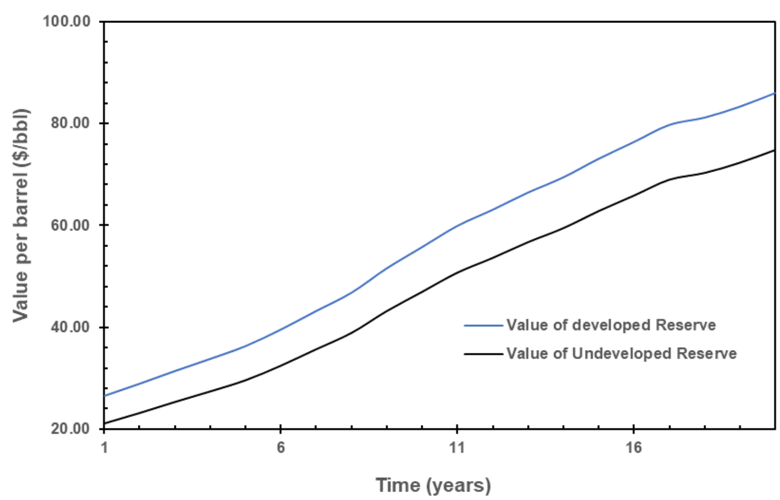

Figure 30. Opportunity cost to exercise the investment option for Waterflooding.

The option value of exercising at a given time, as seen in Figure 31 in color orange, grows with time and hints just like the V* value, to wait for more information before exercising the option. This same behavior is seen in Table 11, where for year one the option value is $65 million and for year five it is $90 million.

The key consideration is the time value of money. If the value of the option is discounted by a rate of 10% (as with the NPV analysis from section 4.1) the discounted option value (blue) in Figure 31 shows a different behavior.

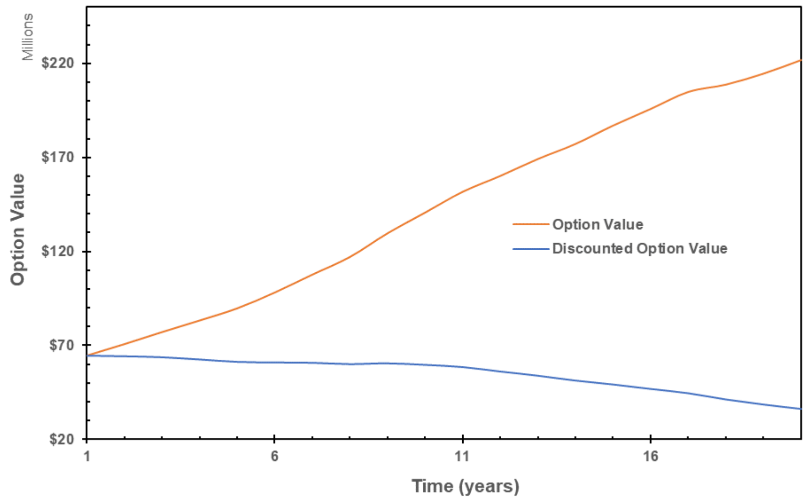

Figure 31. Option Value if exercised at different years undiscounted and discounted for waterflooding.

To clarify further, consider again the option value at year one and year five. The option values are $65 and $90 millions respectively. If we consider the time value of money then Table 11 shows that $65 million today are worth more than $90 millions in five years time, this value would be equal to $61 millions as shown in the table.

In conclusion, even though the option value per barrel increases over time it doesn't increase enough to offset the discount rate. Ultimately, the firm is better off investing right away with the current uncertainty and market conditions considered in the analysis. The option value will then be equal to $65 million.

For the Daatar-Mathews approach, a more mechanical and iterative based methodology is followed. The main concept is to simulate many possible oil price random walks and for each scenario calculate a possible NPV. Mathews (2007) suggest that, depending on the simulated construct, the number of pertinent iterations can be from hundreds to thousands. In this thesis research, one thousand iterations are run for the oil price every year, generating one thousand different oil price behavior scenarios.

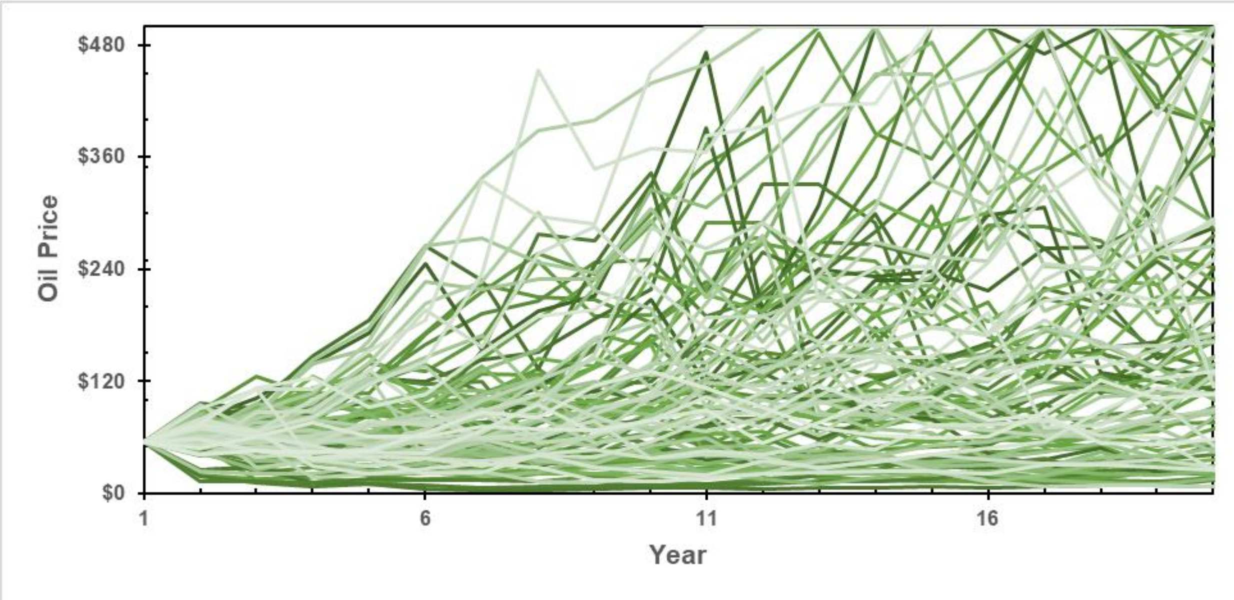

Figure 32. Oil price scenarios simulated with price increments following a Brownian motion process.

The Figure above shows for clarity one hundred of the one thousand different oil price behaviors where random walks with negative oil price were not considered, and where the maximum oil price was capped at $500 to avoid deemed unrealistic scenarios. The whole simulation and linked plots can be found in Appendix G and H, respectively. These random walks were simulated following equation (50) considering a drift in oil price and a Brownian motion increment. The consequences of the oil-price capping is further discussed in section 7.

Figure 33 Illustrates how the uncertainty in the future value of the oil price increases with time. A box plot with whiskers is used to exemplify the notion that, as time passes by, the predictions of the simulations become more uncertain. As mentioned earlier in the methodology section, while the oil price do not follow a normal distribution, its increments or decrements can be assumed to do so. In the case of the oil price, it will follow a lognormal distribution.

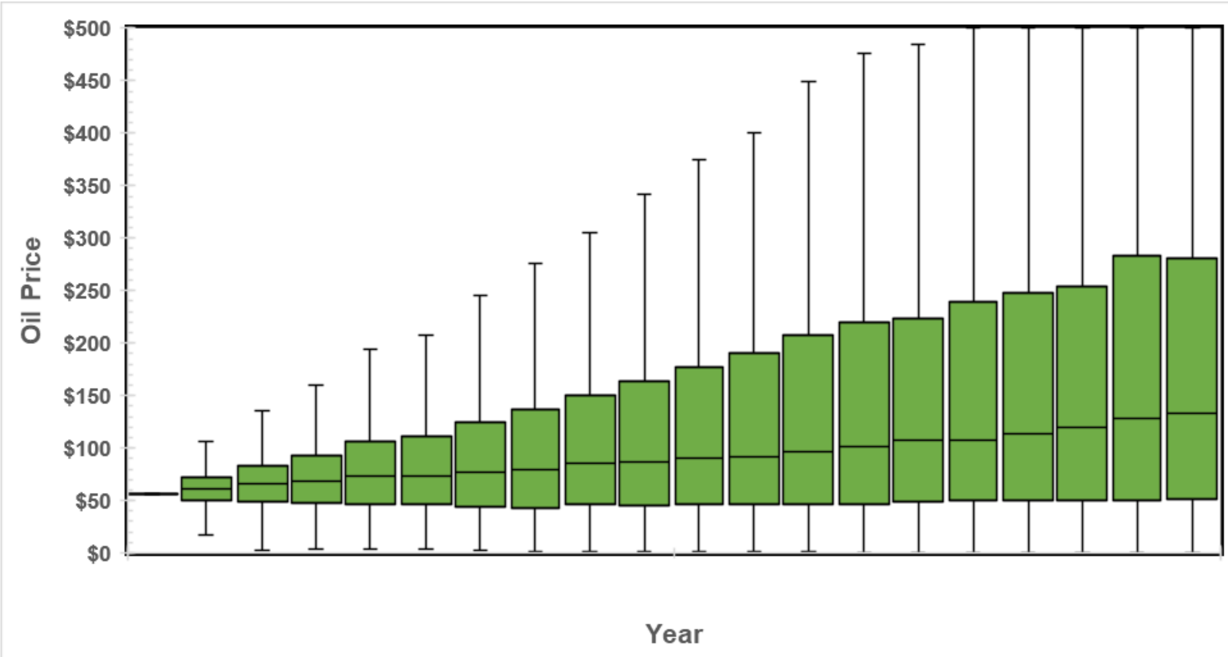

Figure 33. Box and whisker plot of oil price behavior along the years.

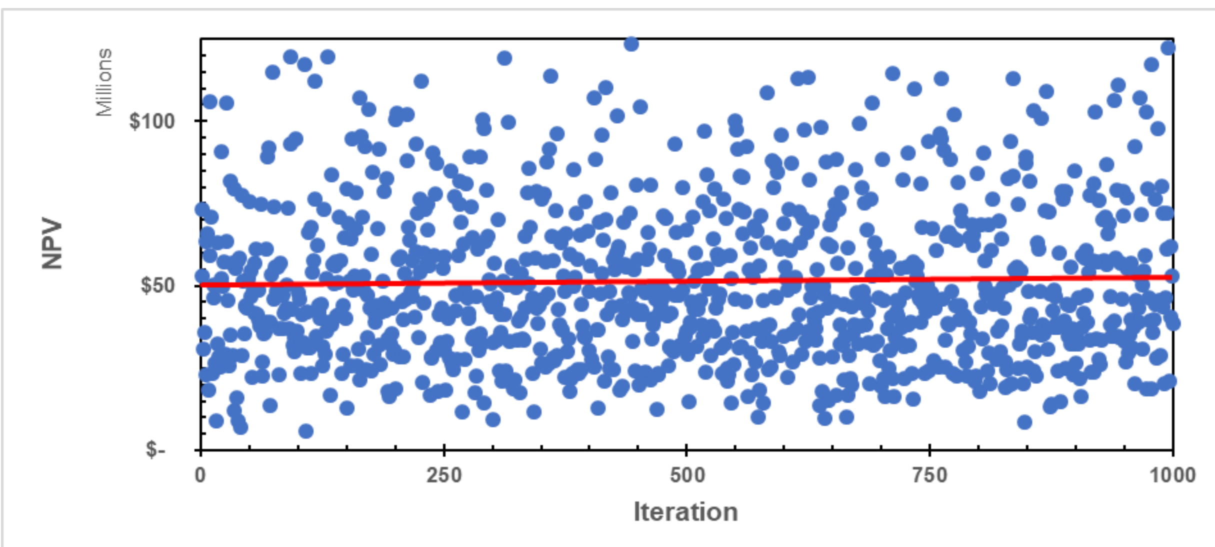

Figure 34. NPV cases from 1000 iterations for waterflooding.

Figure 34 show the calculated NPVs as a result of one thousand different oil price scenarios, where the horizontal axis show the different iterations performed from 1 to 1000 and where each blue dot represents a different NPV case. The red line in the plot represents the mean of the thousand iterations and, as discussed in the Daatar-Mathews approach in section 3.3.11, it represents the option value that should be considered in an economical evaluation. Similarly, Figure 35 shows the probability distribution of all cases found with respect to their NPV. It can also be seen in this figure the mean which represents the option value. For the waterflooding process the mean of the possible scenarios is $51 million.

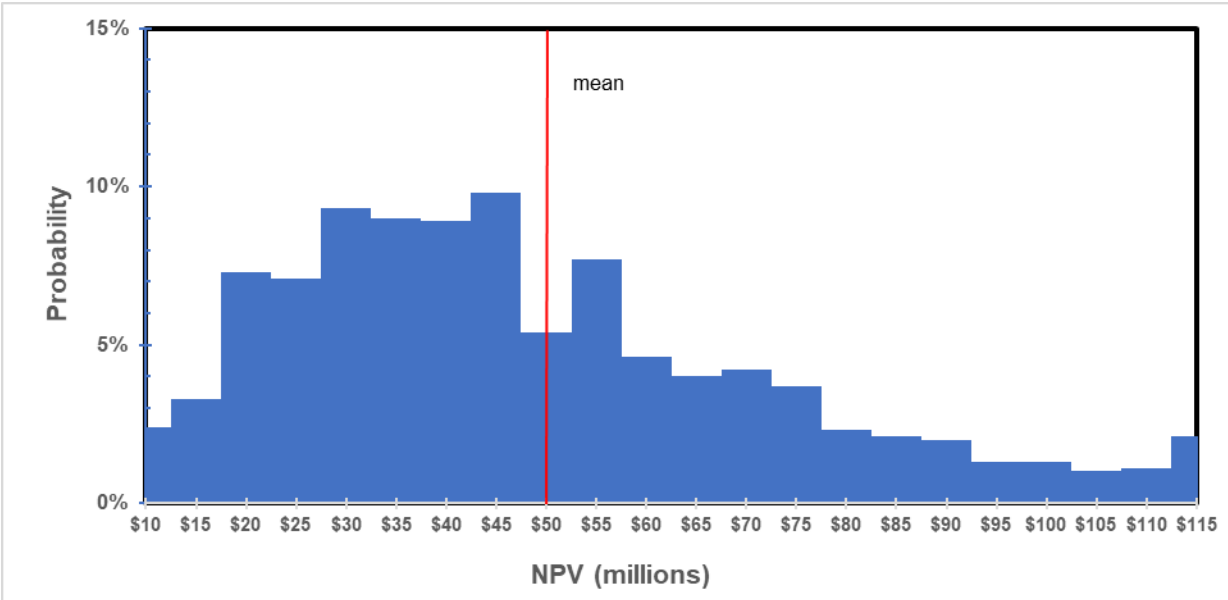

Figure 35. Probability distribution of NPV scenarios.

Table 12 compares the results obtained with the standard NPV analysis and those obtained with the analytic and iterative RO analyses.

Table 12. Economic Analysis and RO comparison for waterflooding.

Analysis	NPV (million)
Standard NPV	$41
Analytic RO	$65
Iterative RO	$51

As Welkenhuysen et al. (2017) and Dixit and Pindyck argues (1994), the standard NPV analysis and even the iterative RO tend to undervalue projects as they don't account for the value of keeping the investment option alive. As seen in the table above, the results are consistent with this notion, showing a higher value with the analytic RO analysis. These three different results will be used later to compare the economic desirability of the two techniques analyzed in this thesis.

5. Polymer Injection Technique

5.1. Economic appraisal

Similar to the last chapter, for the economic appraisal of the polymer flooding technique the methodology described in section 3.3.1 is followed. In order to estimate revenues, the oil production simulation results for the technique will be used. These results can be found in Appendix J. Figure 36 show the oil production behavior of the polymer flooding technique in barrels.

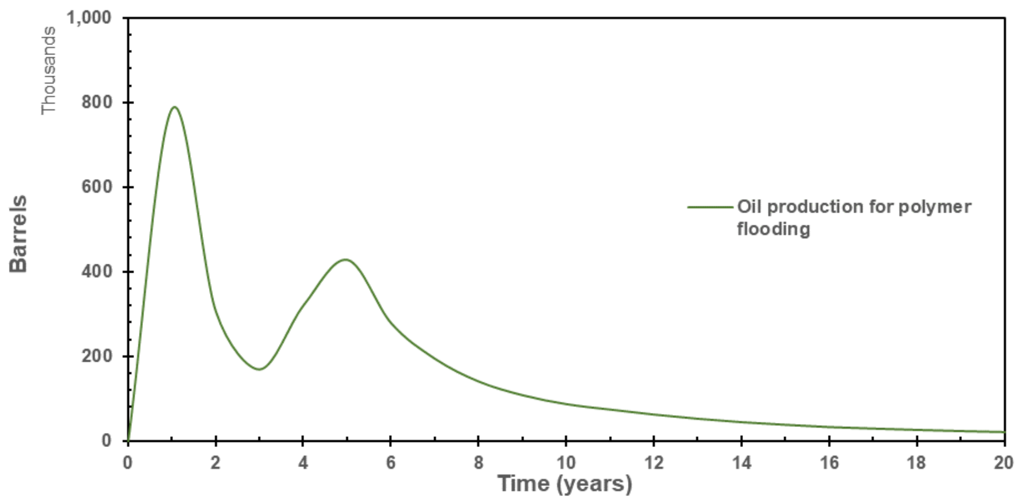

Figure 36. Oil production for the Polymer flooding technique

The figure above shows a different behavior in comparison with the waterflooding technique because, in the polymer flooding, two injection periods are considered. The first injection occurs from year zero and involves only the injection of water, then at year three, polymer is added to the injected stream to improve oil recovery. With the shown additional volumes of oil it is possible to estimate the revenues as previously discussed. In this chapter the whole process of water injection and then polymer injection will be analyze as a standalone project. In the following chapter, section 6 for the comparative analysis, the additional costs, revenues, exergy performance and option values will be considered for the polymer as differentials from the waterflooding base case.

Table 13 show the Capex considered for this technique, as mentioned previously (section 3.3.2), two additional pieces of equipment are considered, a mixing plant and a N_2 blanket generator. The rest of the equipment is considered to be the same used for waterflooding as initially the polymer flooding will inject only water and as a result expect the same production flowrates.

Table 13. Case study scale polymer flooding capital expenditure estimates.

Gross needed injected flow rate	640 m^3/d
Water cut	0.9
Water injection	Assumes all PW is reinjected
Number of producers	8
Number of injectors	8
Flow per injector	80 m^3/d
Gross per producer	80 m^3/d

Box	Item	Number	Capacity per unit (m3/d)	Total Cost (million $)
Separation of produced fluids	FWKO	1	640	0.02
Separation of produced fluids	Booster Pumps	2	76.8	0.28
Separation of produced fluids	Export pumps	2	64	0.32
Separation of produced fluids	Heaters	1	76.8	0.37
Separation of produced fluids	Dehydration Tanks	2	76.8	0.004
Water treatment Plant	Nutshell Filter	1	576	0.19
Water treatment Plant	Backwash System	1	576	0.20
Water treatment Plant	Tanks	1	576	0.12
Water injection	Pumps	1	3600	1.81
Water injection	Manifolds	1		0.40
Water injection	Distribution system	8		2.40
Production Gathering	MSVs	2		0.80
Production Gathering	Distribution system	8		4.00
Producer well cost		8		12.00
Injector well cost		8		8.00
Mixing plant		0.5	640	2.46
	N2 blanket generator	1		0.2
Total Capex				**33.59**

In the case of the opex, Table 6 average values will be used. Together with the capex and additional oil produced, the revenues and yearly cashflows are calculated in Appendix K for the Polymer injection technique.

Just like with the waterflooding technique, the same parameters were considered for the sensitivity analyses shown in Table 3. Table 14 below shows the summarized cashflows considering an IEA oil price scenario 2 and a discount rate of 10%.

Table 14. Cashflows for the polymer technique considering oil price scenario 2 and 10% discount rate.

Year	Discounted Revenue ($ dollars)	Total costs discounted ($ dollars)	Cashflows ($ dollars)
0	$-	$33,594,902.44	$(33,594,902)
1	$39,969,545.95	$4,998,480.97	$34,971,065

2	$15,120,938.03	$3,487,247.67	$11,633,690
3	$8,115,599.01	$2,964,898.06	$5,150,701
4	$14,811,038.59	$3,293,207.89	$11,517,831
5	$18,985,602.12	$2,984,228.52	$16,001,374
6	$11,823,166.06	$2,515,762.98	$9,307,403
7	$7,893,520.91	$2,219,940.97	$5,673,580
8	$5,449,981.44	$1,996,579.01	$3,453,402
9	$3,920,813.05	$1,814,943.87	$2,105,869
10	$2,945,950.44	$1,632,741.16	$1,313,209
11	$2,347,687.55	$1,516,481.35	$831,206
12	$1,839,843.39	$1,381,550.96	$458,292
13	$1,444,206.36	$1,254,525.15	$189,681
14	$1,135,545.59	$1,134,589.13	$956
15	$904,628.22	$1,026,765.94	$(122,138)
16	$719,279.96	$915,708.84	$(196,429)
17	$598,103.18	$842,998.93	$(244,896)
18	$493,341.09	$764,453.23	$(271,112)
19	$409,377.62	$693,485.63	$(284,108)
20	$341,966.98	$629,288.87	$(287,322)
		NPV	**$69,013,358**

It should be noted that from year 15 the estimated cashflows already present negative values. In this thesis, it is assumed that the firm would stop the technique if negative balances are expected and so only positive cashflows are considered for the NPV.

The contribution to the total opex was analyzed for each of its components, the oil handling costs, water handling costs, the costs from the polymer and energy costs. Figure 37, in absolute costs, and Figure 38, in percentage of total costs, show the opex distribution along the years. The costs associated with water handling remains the most important contributor to the expenses along the life of the technique.

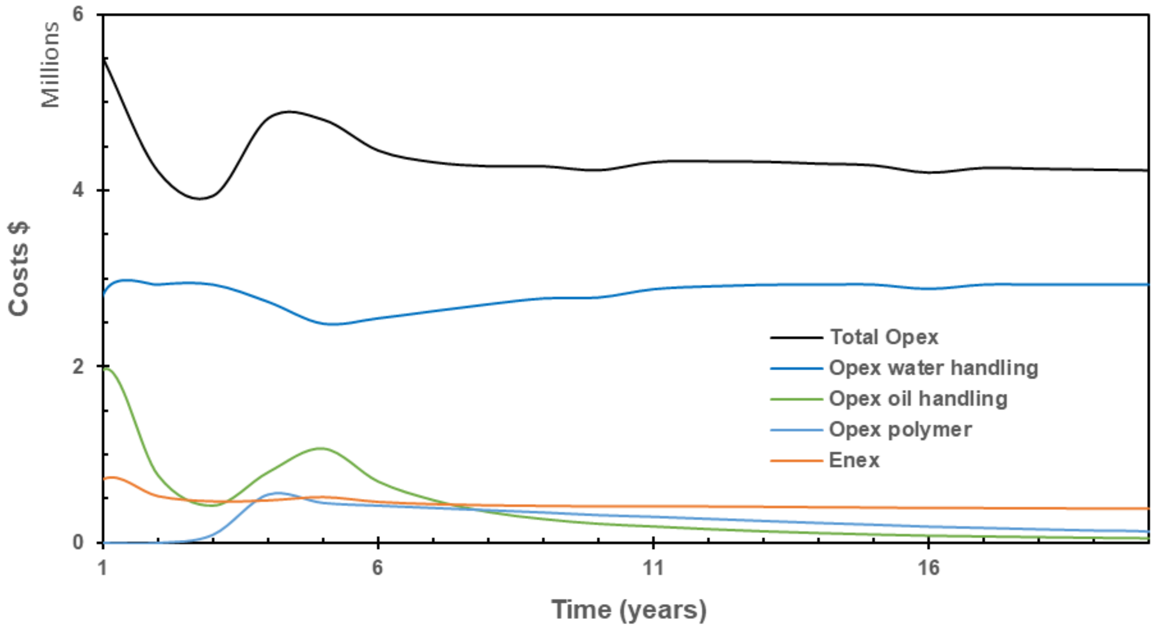

Figure 37. Total Opex and Opex components along the Polymer flooding technique life.

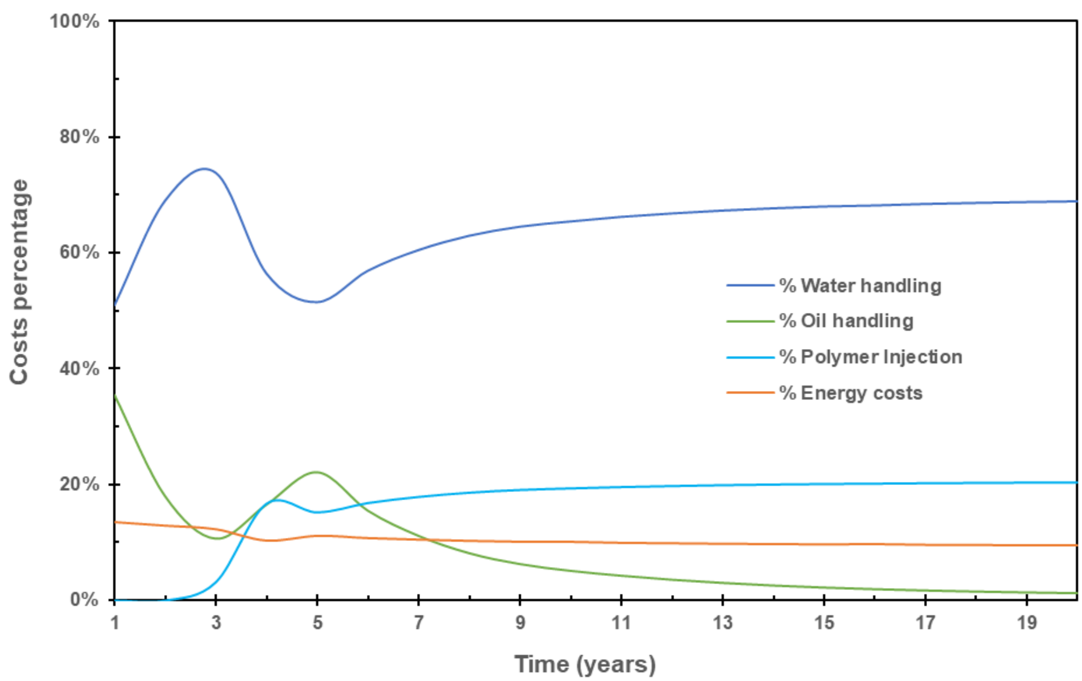

Figure 38. Percentage of Opex components to total Opex along the Polymer flooding technique.

The oil handling expenses follow two high periods where oil production is increased by the injection of fluids. At year one, with water injection followed by a fast decline, then a second high where the polymer injection takes place. At the beginning of the technique the contribution of oil handling is up to 36% of the Operating expenditure while at year 20 it is only 1% of total opex.

In the case of water handling expenditures, it increases from 51% up to 74% as the fractional production becomes more water. As seen in Figure 37, the main contributor to opex is water handling followed by the oil handling expenses. After year one there is a rapid oil decline and thus a lower contribution to opex from oil handling which in turn increases the fraction of water handling contribution. Then after polymer commences to be injected, oil production increases and the water handling contribution to opex remains around 65% for the rest of the techniques life.

In the case of the energy expenditures it remains rather constant accruing to 10% of operating expenditures. As mentioned for the waterflooding, injection volumes remain constant having energy requirements to be almost constant as well. Once polymer injection commences, its costs represent around 20% of total opex for the rest of the technique.

Like the waterflooding technique, three main contributors to the capital expenditures are designed from Table 13: The capex from the wells, the pumps and the rest of the capex. In order to observe the effect of a cost increase in the final NPV, each Capex and Opex component is increased by 10%. Figure 39 shows the % change to the NPV if one of the estimated costs were to be higher. In order of importance, the opex of water-handling is the components with the biggest impact with a NPV decrease of 3%. The main difference with the waterflooding technique is the presence of opex from polymer injection and the increased importance of the water handling in the economics of the technique.

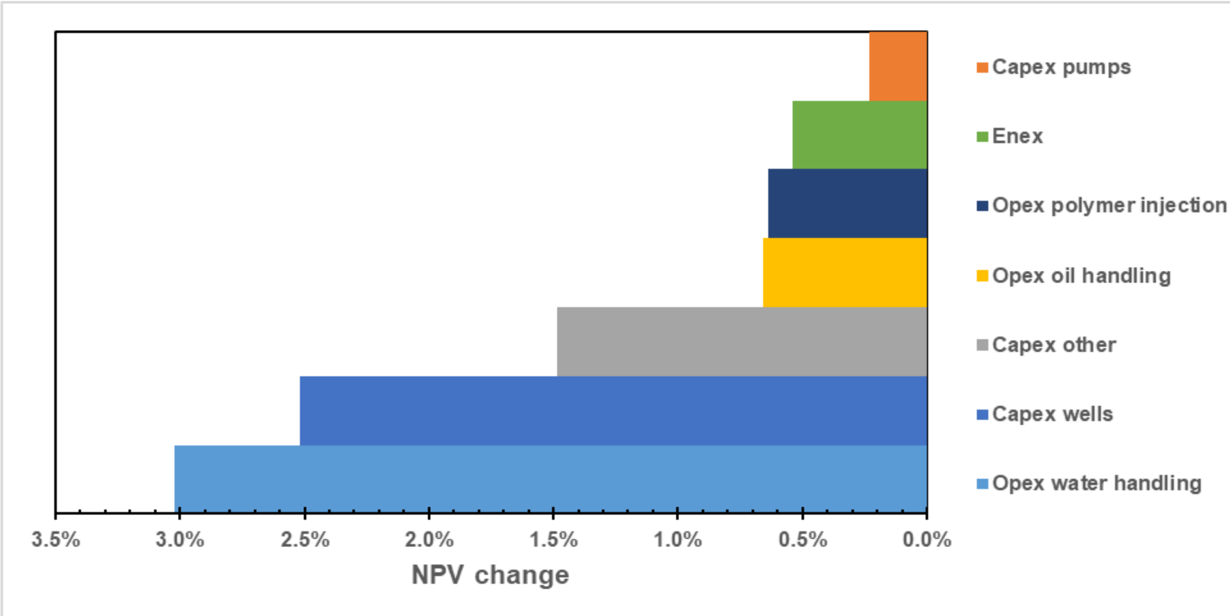

Figure 39. % Change in NPV as a result of 10% increase in an expenditure component for the Polymer flooding technique.

For the discount rate sensitivity analysis, the following results were found.

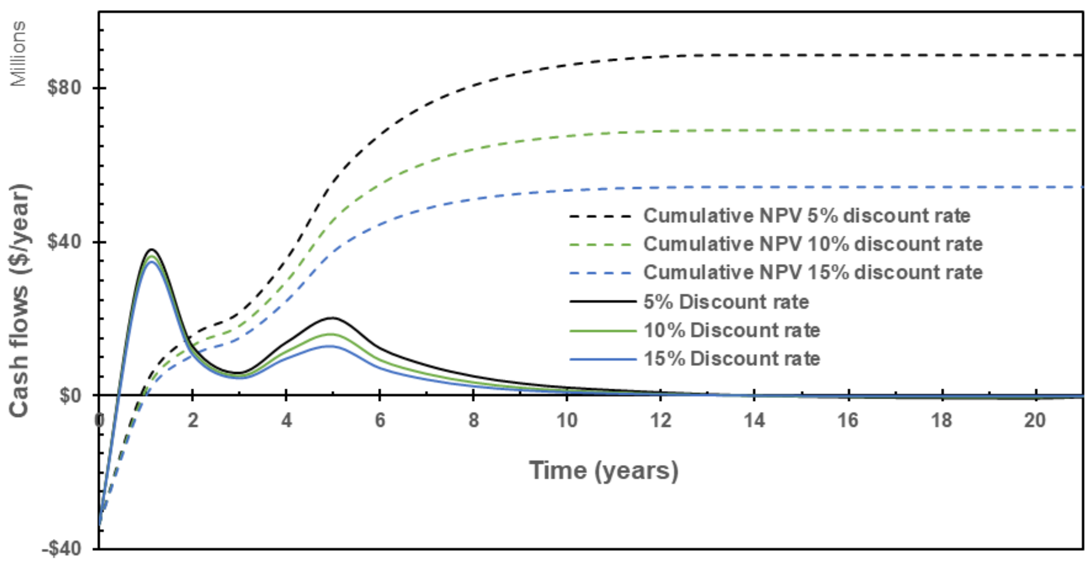

Figure 40. Yearly cashflows and cumulative present value for 5, 10 and 15% discount rates for the Polymer flooding technique.

Figure 40 shows the cashflows per year and the cumulative present value of the different cases, where discount rates are varied. It can be observed in the figure above how the yearly cashflows also present two top points because of the oil production profile.

Between the 10% and the 5% discount rate, the NPV varies as much as 29%. In the case between the 15% discount rate and the 10% discount rate the NPV varies up to 21%.

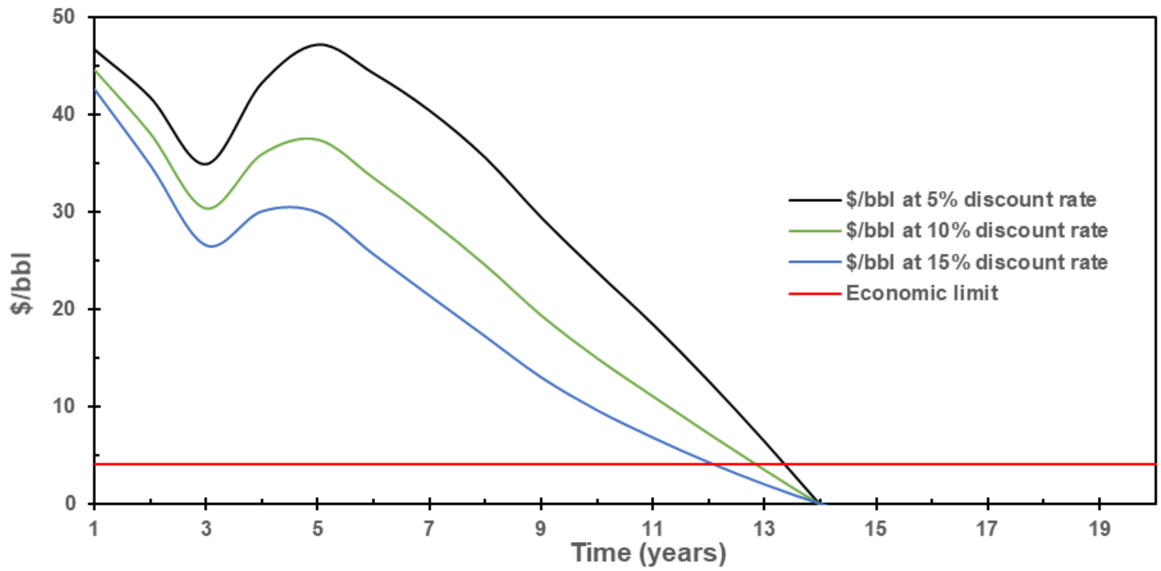

Figure 41. Profit per barrel of oil produced considering 5, 10 and 15% discount rates for the polymer flooding technique.

Figure 41 shows how by year 14 the technique already is not economic. If an economic limit were to be set by the firm, depending on the discount rate used, a slight difference in the uneconomic time is observable.

The sensitivity analysis of the IEA oil price scenarios with a constant 10% discount rate is next discussed.

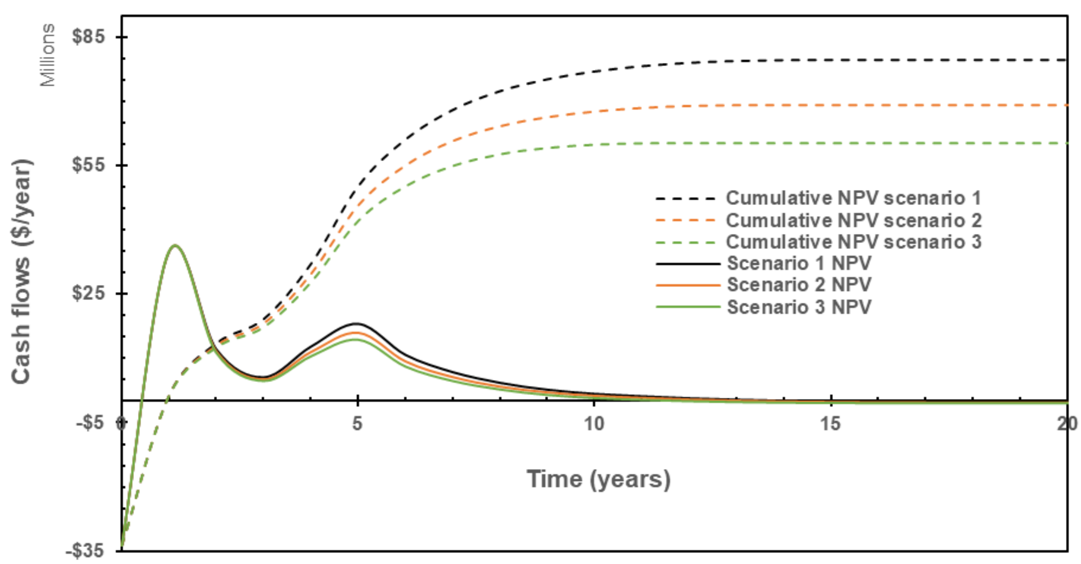

Figure 42. Yearly cashflows and cumulative present value for 3 oil price behaviors following IEA scenarios for the polymer flooding technique.

Figure 42 shows the cashflows per year and its cumulative per each oil price scenario. Since uncertainty increases over the years, the biggest difference on predicted oil price between scenarios are shown at the later years. This notion can be seen in the second peak in cashflows when polymer injection starts. Having an increase in oil production in later years causes the cumulative to vary more if compared to the waterflooding technique.

In the case of scenario 1 and scenario 2 a difference of 15% is observed in the final NPV. Similarly, between the scenario 2 and scenario 3 a difference of 13% is observed.

Figure 43 show how the different oil price scenarios can affect the profitability of the technique. For the Scenario 3 or that of "sustainable development" the technique becomes uneconomic as soon as the 12th year while a more optimistic oil price scenario like scenario 1 keeps the technique economically viable three more years.

Figure 44 is a summary of the nine conditions considered for the sensitivity analysis in this section. Similar to the waterflooding, the change in final NPV is shown variating discount rate and oil-price scenario. The importance of this results is to visualize the effect of selecting different discount rates and the effect of different oil-price behaviors.

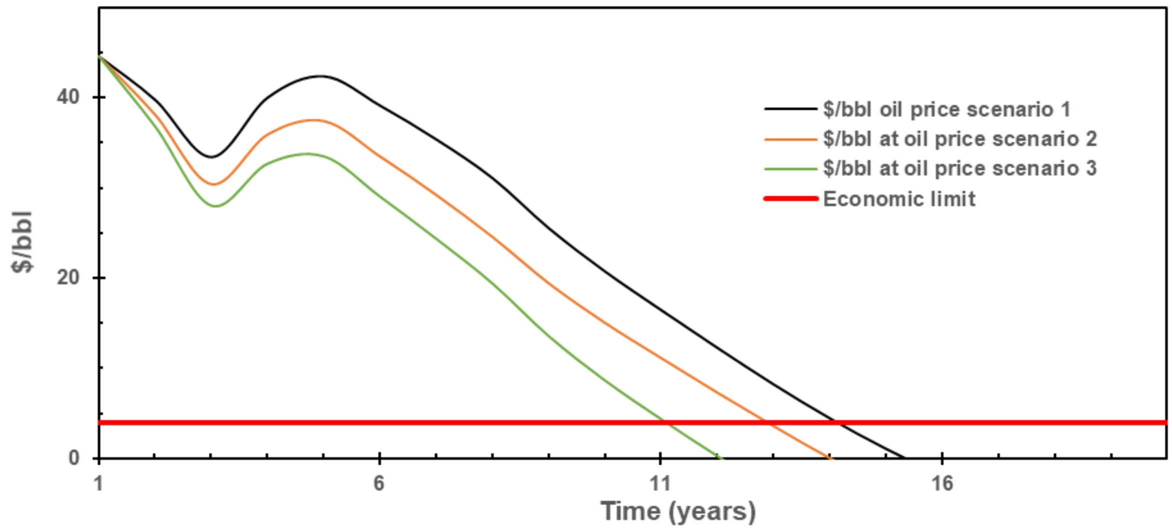

Figure 43. Profit per barrel of oil produced considering three different oil price scenarios by the IEA for the Polymer flooding technique.

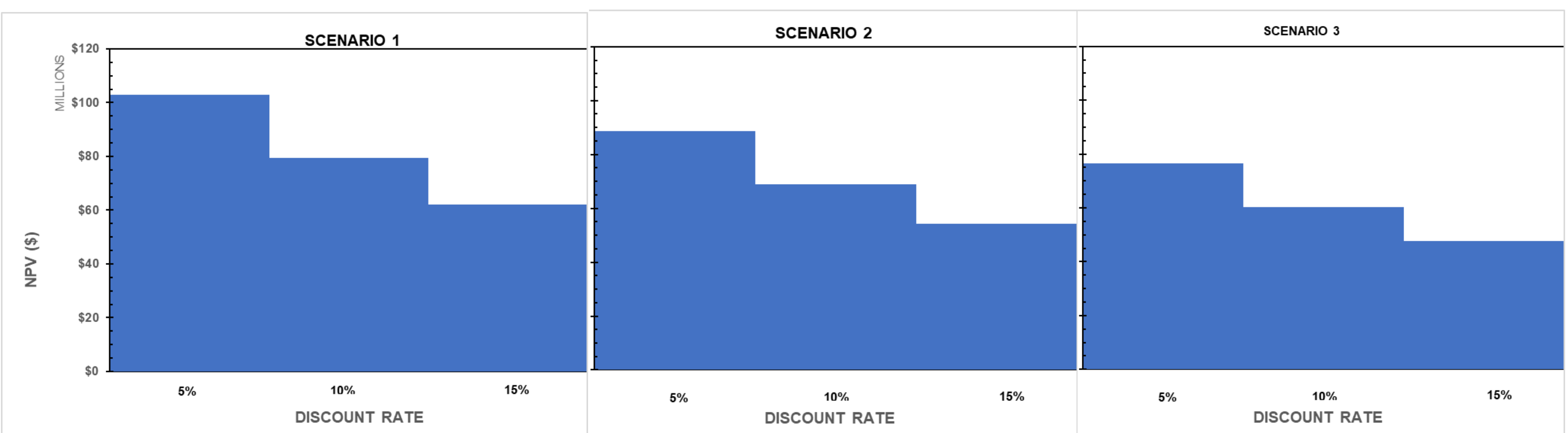

Figure 44. Sensitivity analyses summary for discount rates and oil price behaviors for the Polymer flooding technique.

5.2. Exergy analysis

Figure 10 show the component layout for the polymer injection technique. Following this layout and the methodology described in section 3.3.3, the Exergy product, Exergy Fuel and Exergy Destroyed are calculated in appendices L and M for the polymer flooding. Table 15 summarizes the results obtained.

Table 15. Product and Fuel Exergy summary for polymer flooding

Components	Pump A.1	Pump A.2	Pump A.3	Pump Atot	Heater and separator	Dehydration	Water treatment	Total
Ph Exergy i (W)	174,768	385,217	-500,125		88,954	-98,580	0	
Ch Exergy i (W)	0	61,119,790	0		0	0	-186,001	
Total Product Exergy	174,768	61,505,007	-500,125	61,179,651	88,954	-98,580	-186,001	61,170,025
Exergy Fk (W)	0	99,922	132,699	232,621	314,154	0.0003	310,895	857,670
Exergy Dk (W)	0	0	632,824	632,824	225,200	98,580	496,895	1,453,500
yD				**44%**	**15%**	**7%**	**34%**	

It is important to mention that the chemical exergy considered to be lost due to the disposal of the polymer material is included in the chemical exergy calculations (Ch Exergy) shown in the table above.

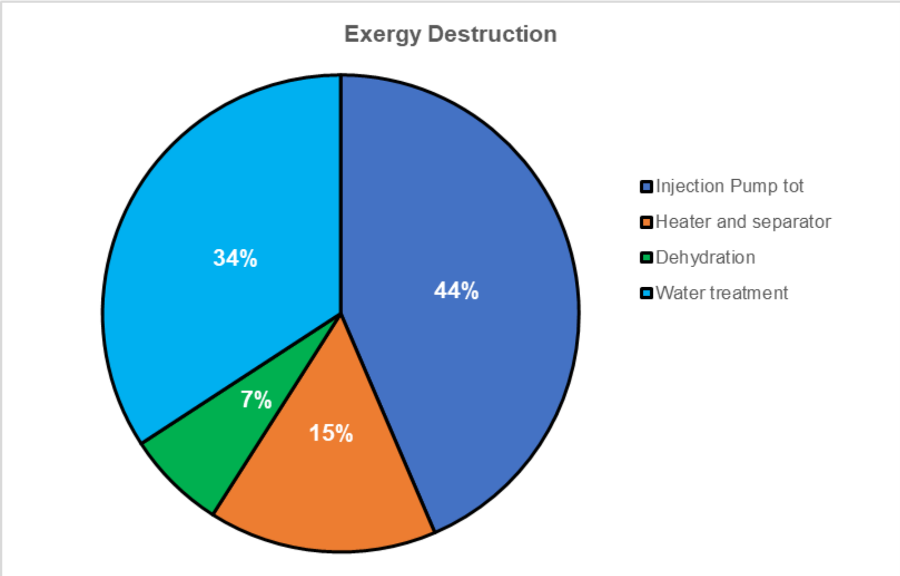

Figure 45. Exergy destruction contribution per energy carrier for the polymer injection technique.

Figure 45 shows visually how the Exergy destruction is distributed in the equipment units. The major contributor n lies in the injection pumps, similar to the waterflooding technique. It is to be noted a decrease in Exergy destruction contribution from the pump in comparison to the waterflooding. This is in part because the amount of pumped water needed is less when polymer is added. On the other hand, the contribution to the Exergy destroyed from the treated water increases, mainly because the chemical exergy of the polymer is deemed as destroyed after water treatment since no water or polymer is recycled in this technique.

Figure 46 show the Exergy fuel and Exergy destroyed along the life of the technique. Similar to the oil production profile, there is a second increase right when polymer injection commences. As mentioned above, this increase in Exergy destruction comes from the increase in produced fluids as well as with the disposal of the polymers after water treatment.

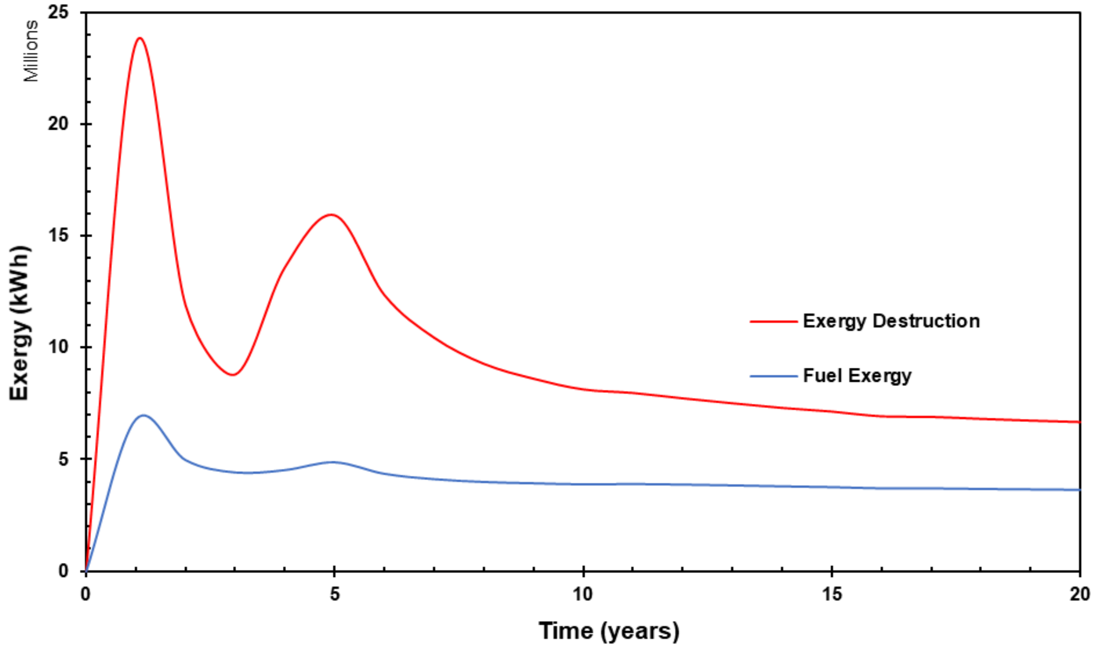

Figure 46. Fuel Exergy and Exergy Destruction for polymer flooding.

In the case of the Exergy Product, as with the previous technique, it will increase in relation to the amount of oil being produced. Because of this, Figure 47 shows a similar behavior with the oil production along the years. After the injection of the polymer, an increase in Exergy product is observed followed by a steady decline.

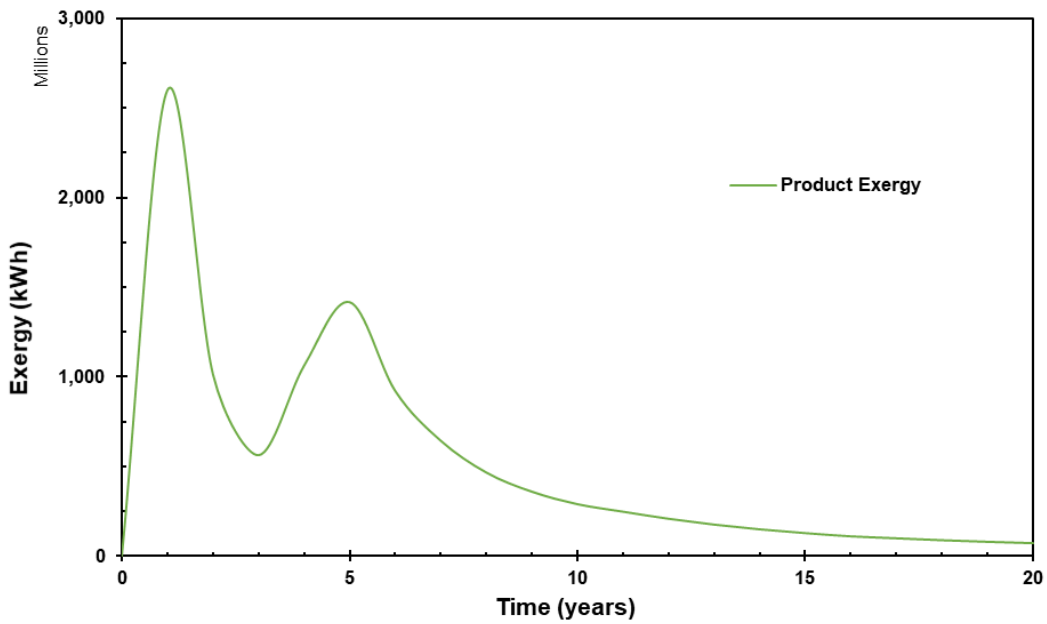

Figure 47. Product Exergy for polymer flooding.

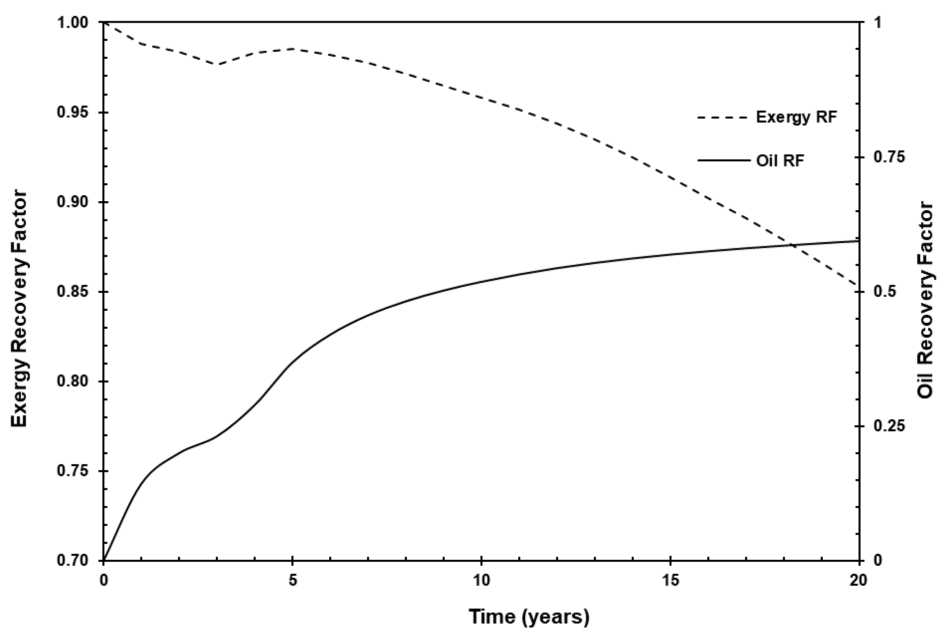

Figure 48. Exergy Recovery Factor for polymer flooding.

Figure 48 shows how the Oil RF increases to a maximum of 59% after year 20, showing an abrupt increase after polymer injection and a slower increase at the final years. The exergy RF actually increases after the polymer is injected but also experiences a rapid decline as oil production is reduced. The ERF at year 20 is 85%.

As seen in the previous figure, the efficiency of the technique is reduced with the years. Following that trail of thought it becomes clear that the needed invested kWh per barrel produced increases as well with the years.

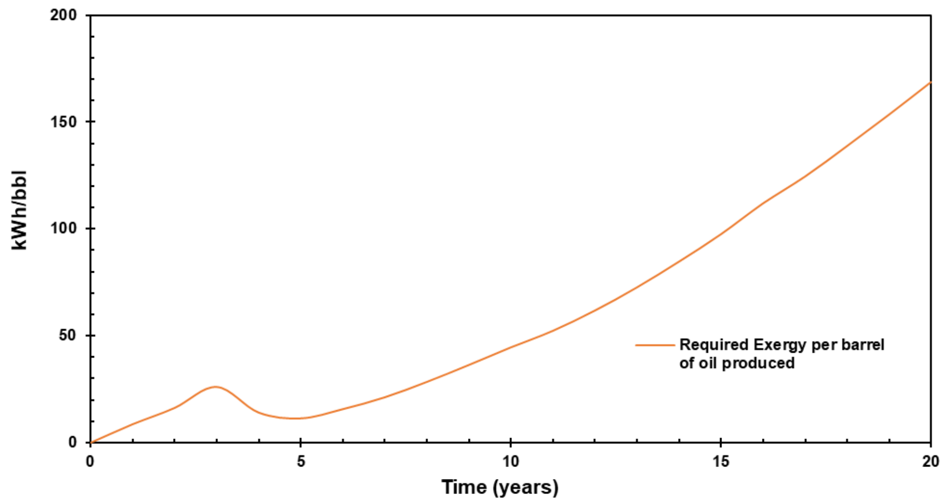

Figure 49. Required Fuel Exergy per barrel of oil produced for the polymer flooding.

It is seen in the figure above how the injection of polymers after year three makes the oil production more efficient but the needed kWh to produce one barrel of oil increase fast with time.

Figure 50 shows how the cumulative net Exergy also has a similar behavior to that of the cumulative cash flows. The incremental revenues and incremental Exergy recovered decrease in the late years to a point where they get close to constant, as this occurs, the profitability of the project decreases and so does its exergetic efficiency.

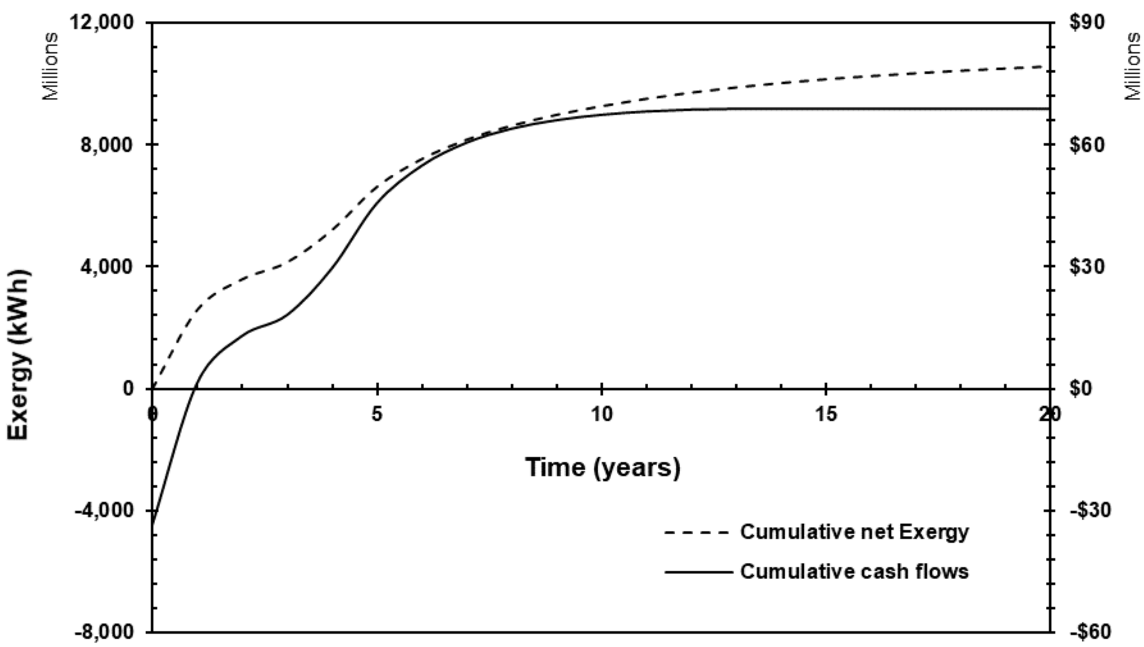

Figure 50. Cumulative net Exergy and cash flows for the polymer flooding.

The full Exergoeconomic analysis for the polymer injection technique can be found in Appendix N. Next, the main results are discussed.

At the beginning, the Product Exergy cost rate is up to $3800 per hour due to an increase in Capex. From year two onwards the hourly cost of the Product Exergy is $350 where only Opex is considered in the factor Z. This represents almost four times the cost rate if compared to the waterflooding technique.

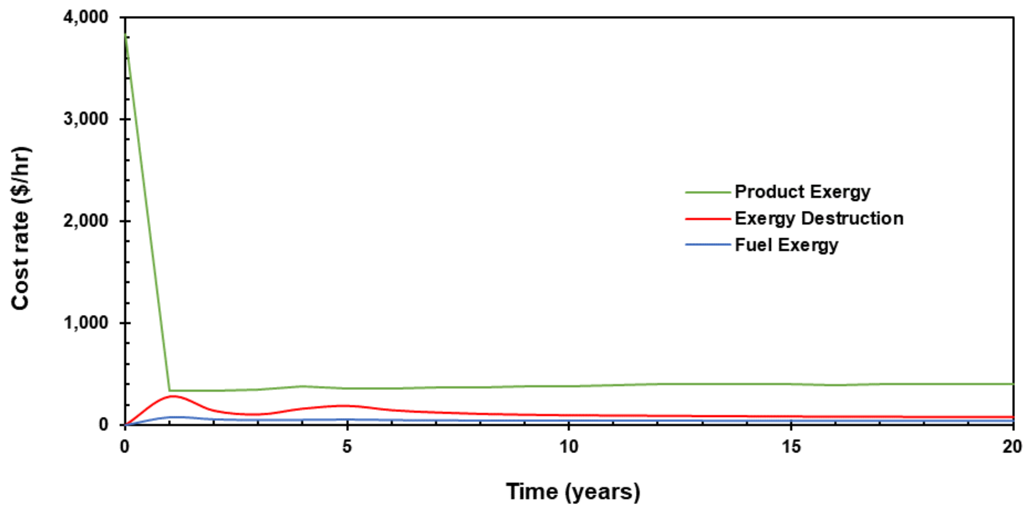

Figure 51. Cost rate of Product, Fuel and Destroyed Exergy for polymer injection.

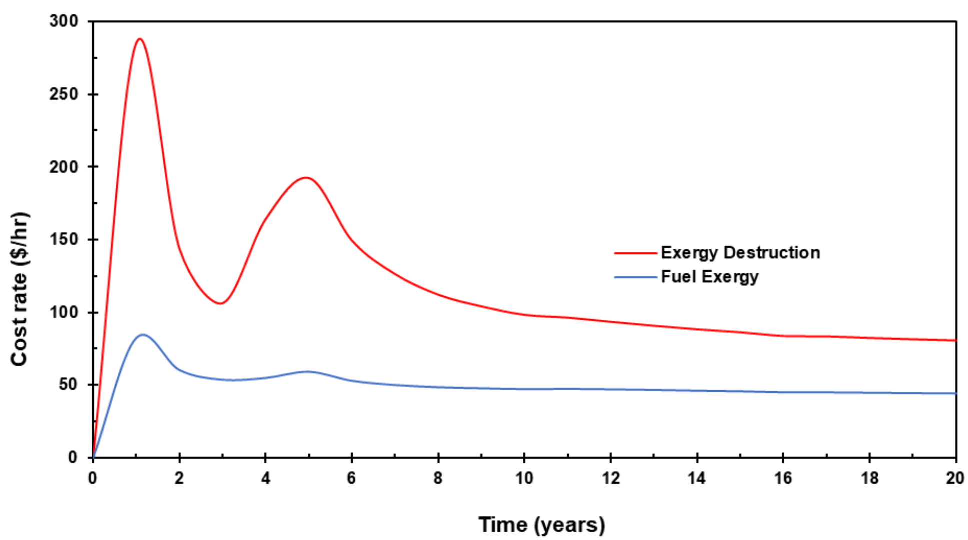

Figure 52. Cost rate of Fuel and Destroyed Exergy for polymer flooding.

The Exergy Destruction varies mostly at the beginning of the technique because its cost rate is related to the amount of Exergy that is destroyed in the energy carriers. Also, after polymer is injected, an increase in the cost rate is observed as more Exergy is destroyed.

Figure 51and Figure 52 show the Exergy cost rate behavior along the years for the polymer flooding technique.

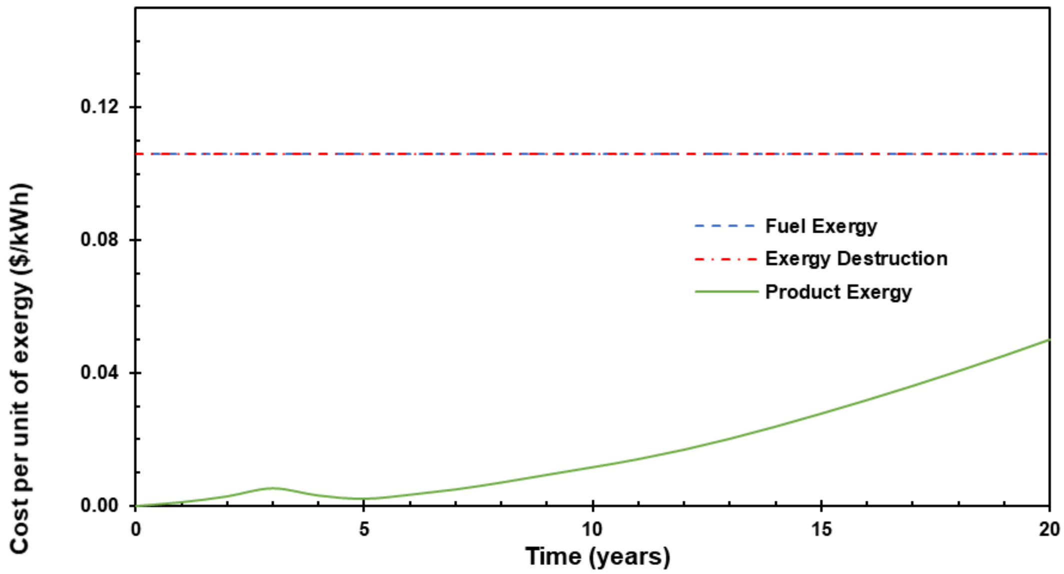

Figure 53. Cost per unit of Exergy for Fuel, Product and Destroyed Exergy for polymer injection.

As it can be seen in Figure 53 the cost per kWh recovered increases over the years due to a declining efficiency. The Destroyed Exergy is costed the same as the Fuel Exergy assuming a constant price per kWh. The Exergy parameters described can as well be used to compare competing techniques in relation to their efficiency performance.

5.3. Real option value

In this section the Real option value of applying the polymer flooding technique will be obtained following the analytic RO approach and the simulation approach.

Table 16 summarizes the results of the analytical RO analysis and for brevity, presents them for years one, five, ten and twenty. The complete analysis can be found in Appendix O.

Table 16. Analytic RO results summary for polymer injection.

Year	P ($/bbl)	V ($/bbl)	V* ($/bbl)	F(V) ($/bbl)	Option value undiscounted ($ millions)	Option value discounted ($ millions)
1	56	26	62	18	75	75
5	77	36		26	109	74
10	115	53		54	173	73
20	188	88		78	306	50

For the polymer injection oil-recovery technique, just as shown in Table 7, a % value per barrel of oil was found to be 47% and a profit of 57% per barrel.

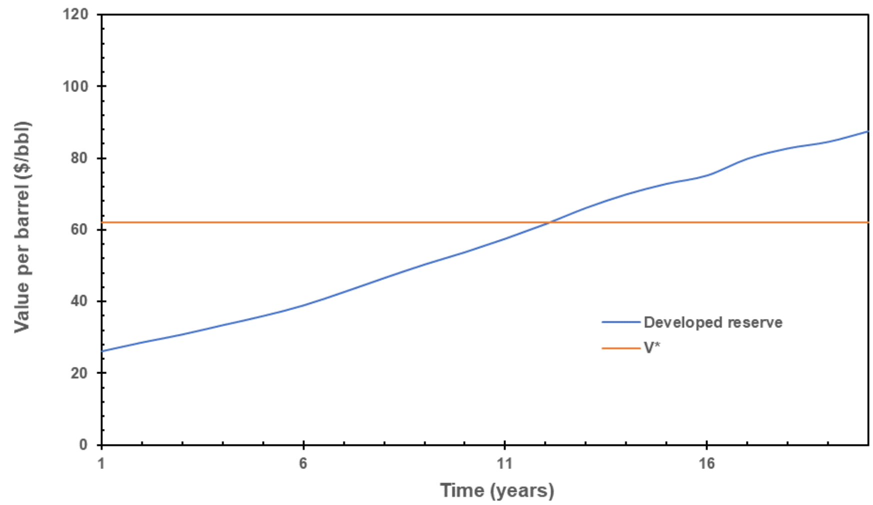

Figure 54. Optimal investment value and developed reserve value for the polymer flooding technique.

The picture above shows that, if the oil price follows the expected random walk, it would reach the optimal value V* at year 12 and recommends then to not exercise the option right away, as waiting would be of more benefit. This result again must be assessed with care as the value of money should be taken into account. Similar to the waterflooding technique it is shown in Figure 55 that even though the option value grows with time, the discounted value actually decreases due to the discount rate.

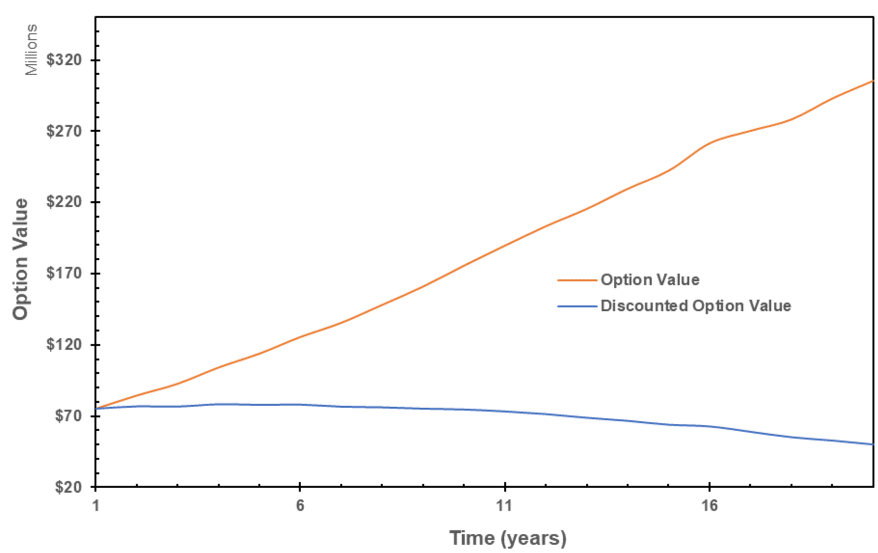

Figure 55. Option Value if exercised at different years undiscounted and discounted for the polymer injection.

The firm will then be better of investing right away. The option value is then equal to $81 million.

For the Daatar-Mathews approach, this technique will use the same methodology to generate 1000 iterations of Oil price random walks where oil price increments follow a Brownian motion as seen in Figure 32.

The whole simulation for this technique and linked plots can be found in Appendix P and Q, respectively. The following figures show the NPV distribution as a result of the 1000 iterations and a line in the mean of the scenarios. This mean, as the Daatar-Mathews approach recommend, should be considered as the option value of the technique. In this case the iterative approach gives an option value of $86 million.

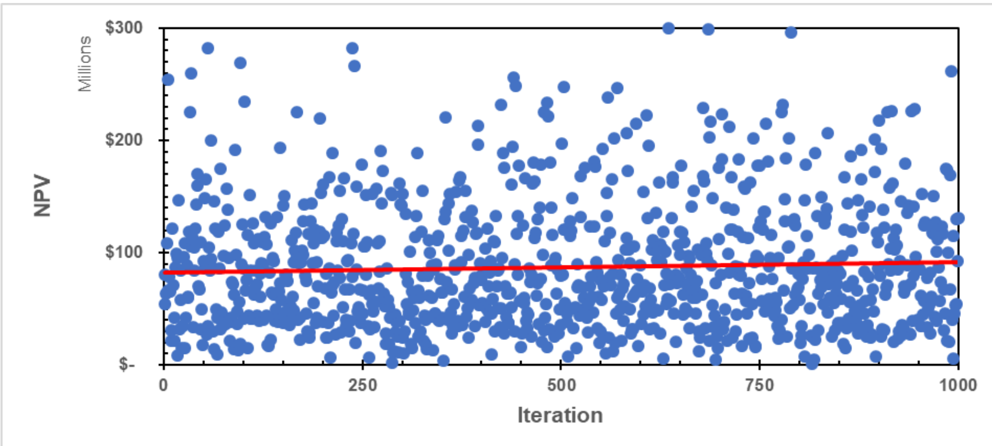

Figure 56. NPV iterations distribution for the polymer flooding.

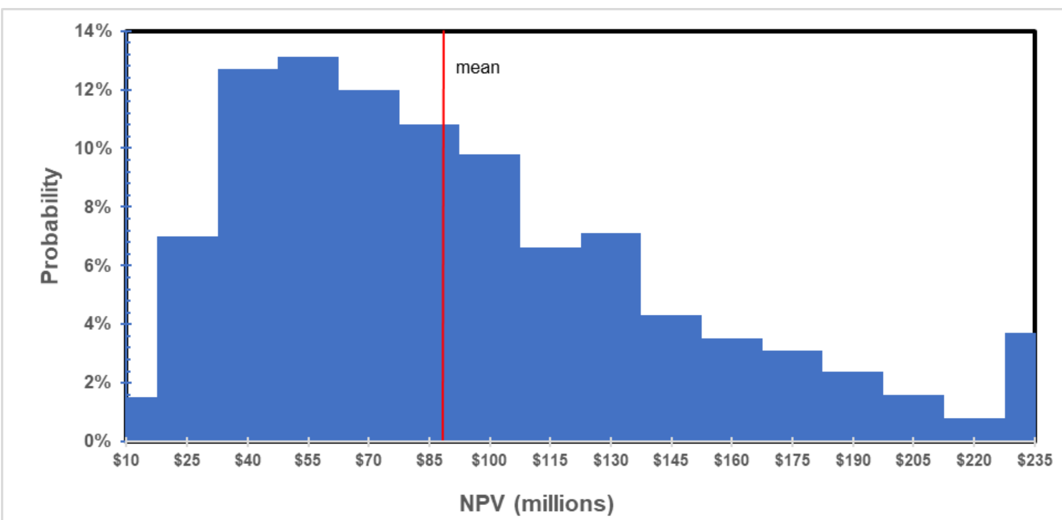

Figure 57. Probability distribution of NPV scenarios for polymer injection.

Table 17 compares the results obtained with the standard NPV analysis and those obtained with the analytic and iterative RO analyses for the polymer injection.

Table 17. Economic Analysis and RO comparison for polymer flooding.

Analysis	NPV (million)
Standard NPV	$69
Analytic RO	$75
Iterative RO	$86

It can be seen in the table above that for this technique a higher NPV is obtained with the iterative RO approach but very similar to the analytic approach. As discussed by Dixit and Pindyck (1994) Real Options are able to capture not only the benefits of the expected returns but also the opportunity costs often ignore with conventional NPV approaches.

6. Comparative analysis

In this chapter the differences between the techniques and their performance will be analyzed and discussed. First, the oil production along the years is shown for both techniques to illustrate their differences. As can be seen in Figure 58 and Figure 59 both techniques have an identical production profile in the first three years and then, when polymer injection begins for the second technique, additional production is obtained.

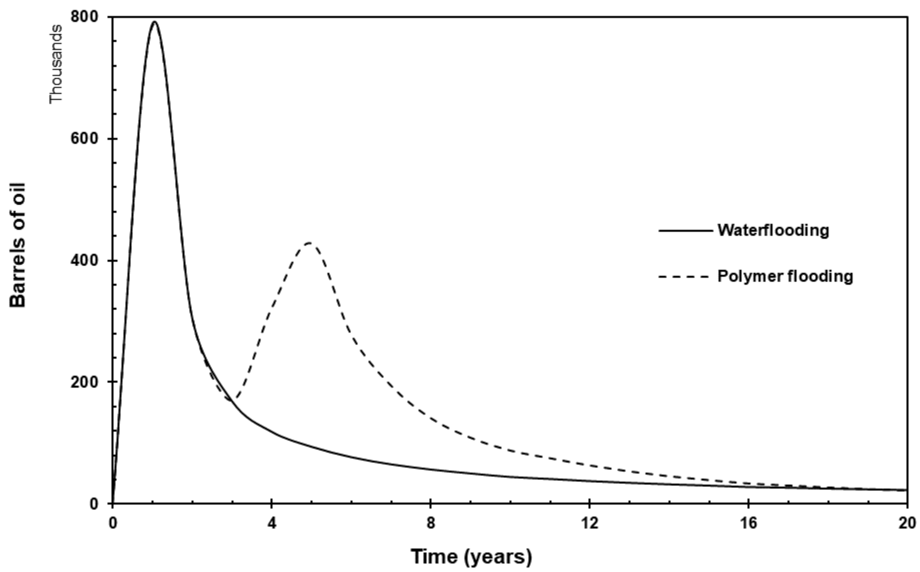

Figure 58. Oil production comparison between waterflooding and polymer injection.

As discussed in section 1, two situations are being analyzed in this thesis, one is to inject water to the reservoir and continue till year 20 and the second is to first inject water and at year three start pumping water and polymer product. In the previous section, the second approach was analyzed from year one in a standalone fashion in order to assess its performance with the NPV rule, exergy and real options. In this chapter, since the polymer injection will be compared to the waterflooding, only the differential values will be shown. Since both approaches are identical from year zero to year three from this point all graphs will start from year three and highlight the polymer injection differential values from the waterflooding base case.

In Figure 59, the highlighted area represents the amount of additional oil that is produced due to the injection of polymer after year 3 in comparison to the waterflooding technique.

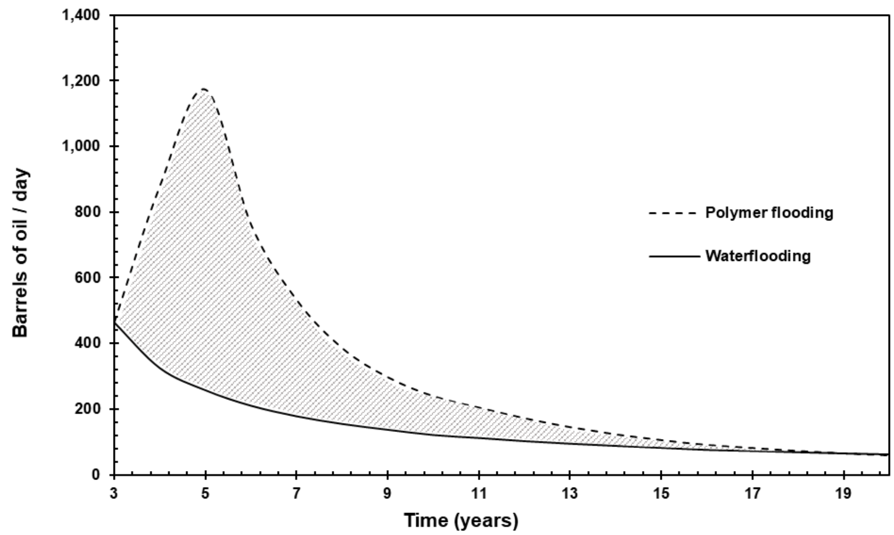

Figure 59. Additional oil recovered for polymer injection in comparison to the waterflooding case.

It becomes evident that the cashflows will be more favorable for the polymer flooding technique considering almost an additional 1 million barrels of oil production along the techniques life. But such increase in revenues comes with increased costs and additional Exergy invested and destroyed as will be discussed in the following sub-chapters.

6.1. Standard NPV

As hinted above, there is an increase in invested capital and operating expenditures for the polymer injection technique in comparison to the waterflooding. As seen in Figure 60 and Table 13, the increase in capital expenditures comes from the additional equipment needed and amounts for as much as $3 million. The additional operating costs introduced by the use of polymer and from the higher requirements from processing and disposing water and polymer accrue to as much as $12 million. This shows that the biggest increase in costs would come from operating expenses.

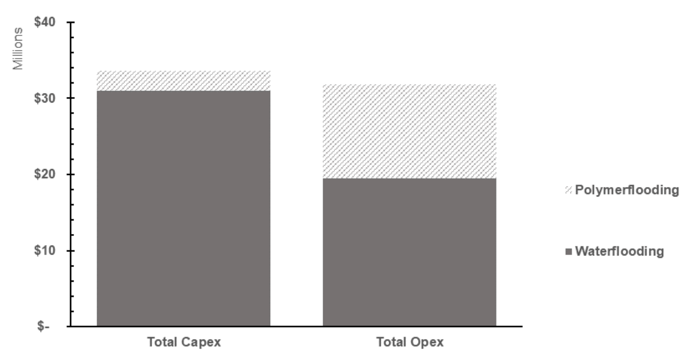

Figure 60. Additional Opex and Capex for the polymer injection in comparison to the waterflooding technique.

Figure 61 show how the cumulative cashflows, similarly to oil production, increase for the polymer injection. A 10% discount rate and an oil price IEA scenario 2 is used to make the comparison. The difference seen during the first years with a lower return for the polymer flooding is due to higher Capex in comparison to waterflooding.

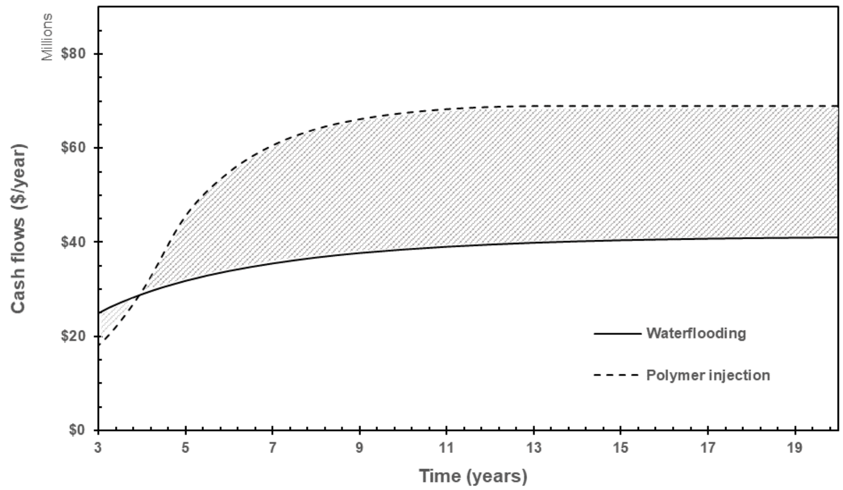

Figure 61. Increase in cumulative cashflows per year for polymer flooding in comparison to waterflooding.

The effect on higher Capex and Opex for the polymer injection is perhaps more visible in Figure 62 where it can be seen that by year 14 the Polymer injection is already uneconomic while the waterflooding process continues for the 20 years.

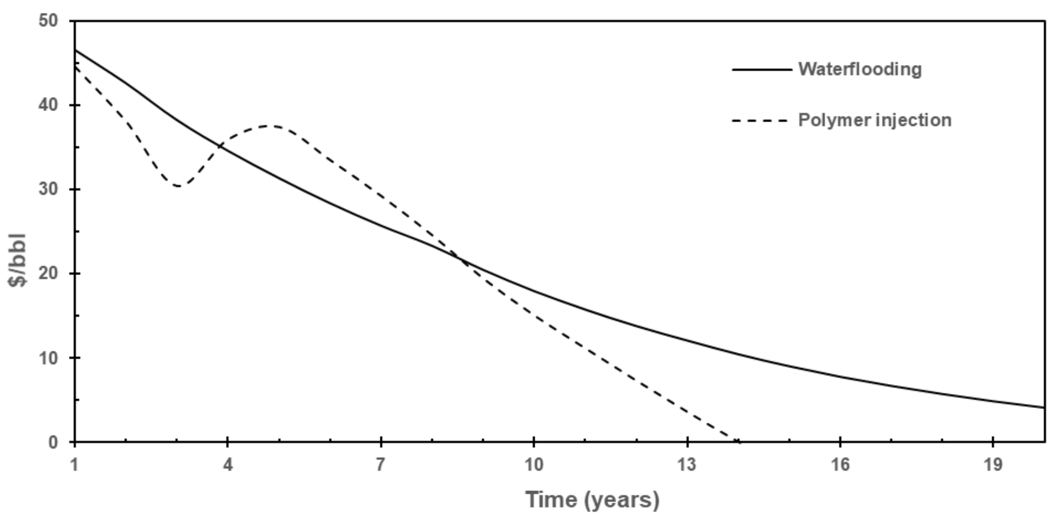

Figure 62. Profit per barrel of oil produced for the two techniques.

The final NPV obtained for both techniques are summarized in Figure 63 and Table 18.

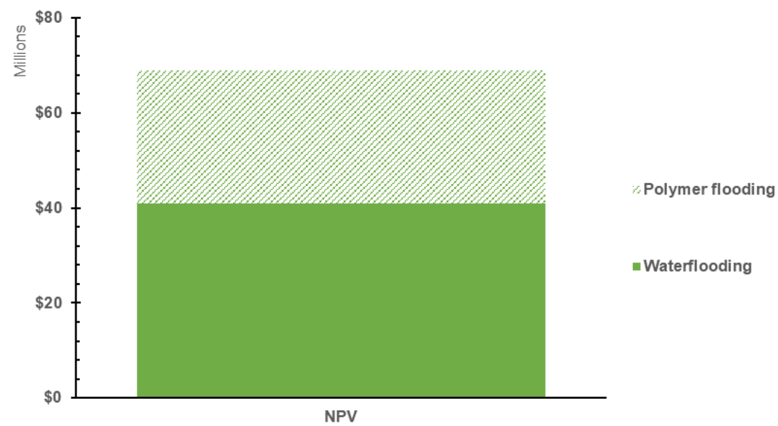

Figure 63. Additional profits for the polymer injection with regards to waterflooding.

Table 18. Differential NPV for Polymer Injection.

Analysis	Polymer Injection
Standard NPV (millions)	$28

As shown in the table above despite reaching early unprofitable values, the polymer flooding still present a higher NPV with an additional $28 million profit and is thus the preferred technique in this analysis.

6.2. Exergy and Exergoeconomics

For the Exergy and exergoeconomic comparison, the following parameters will be considered. Exergy Recovery Factor, Exergy destroyed, Exergy Fuel, Exergy Product, Exergy Return on Investment, ExD/ExF ratio and the cost rate of the Exergy product. Considering the waterflooding as a base case and the additional exergy values from this will be used to calculate the ratios as increments due to the application of polymer injection.

For the Exergy Recovery Factor (Figure 64 and Figure 65), right after polymer injection starts, the ERF for polymer flooding out-performs the waterflooding technique up to year 15. After this moment, the polymer injection shows a less efficient performance than waterflooding. Considering the whole life of the technique the polymer injection outperforms the waterflooding only by 4 percentage points. As will be shown next and following equation (34), the Exergy recovery factor is a function of the Exergy product, exergy fuel and exergy destroyed.

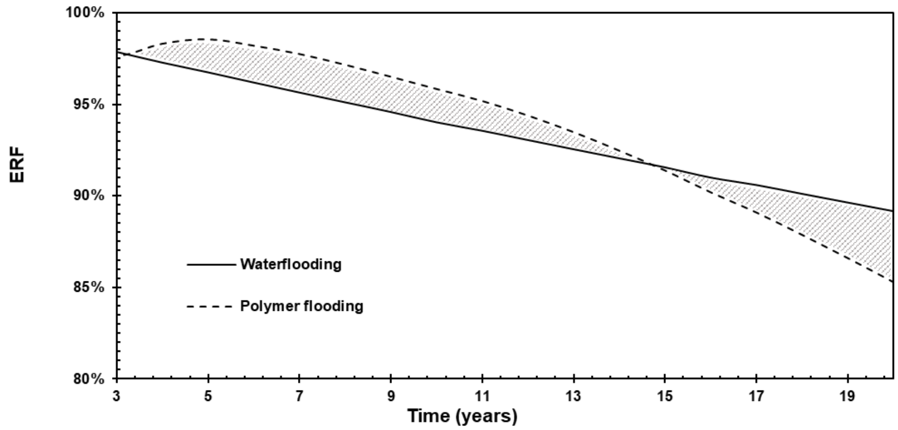

Figure 64. Exergy recovery factors comparison per year basis.

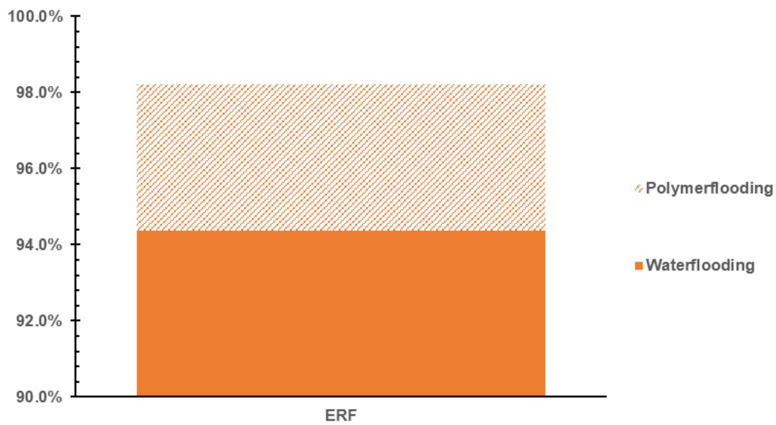

Figure 65. Exergy RF difference for the whole techniques life.

In order to analyze further the ERF behavior, the amount of destroyed Exergy for both techniques is compared in Figure 66 and Figure 67. It can be seen in these figures that more Exergy is destroyed in the polymer injection technique per year and ultimately more total destroyed exergy with an additional 61 GWh at the end of the techniques life. This is a result of the additional physical and chemical exergy destroyed in the material streams, including the disposal of the injected fluids.

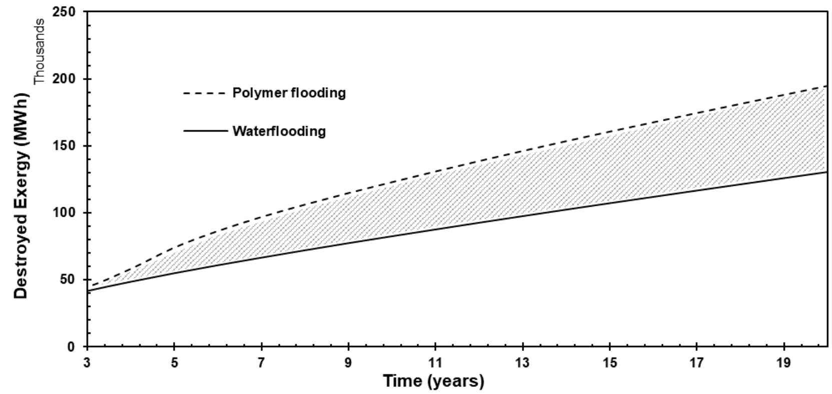

Figure 66. Cumulative destroyed exergy for both oil-recovery techniques.

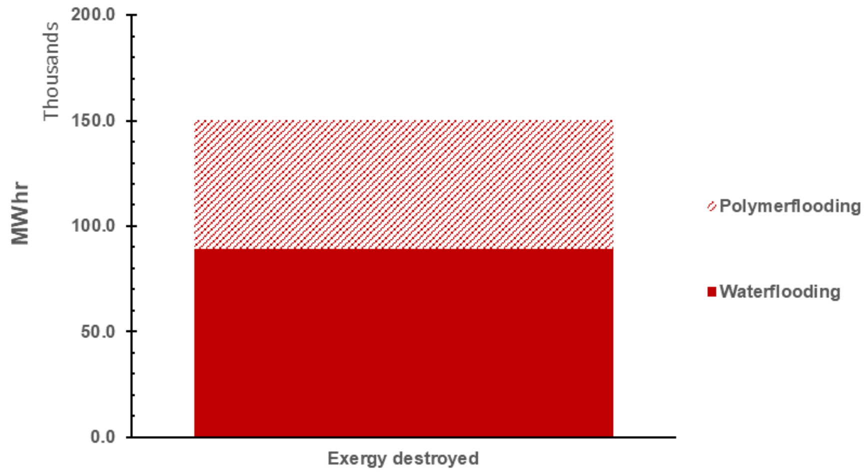

Figure 67. Total additional exergy destroyed at the end of year 20 for both techniques.

Figure 68 shows how the polymer flooding invests more Exergy fuel in comparison with the waterflooding, as more oil is produced, more exergy needs to be invested in the pieces of equipment to handle production.

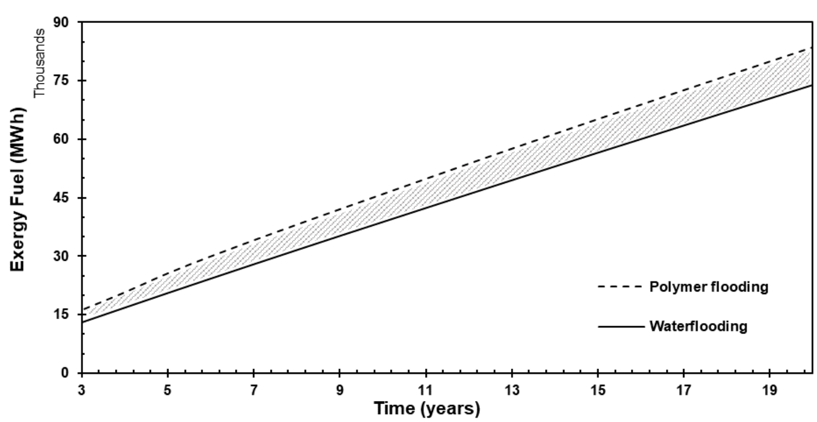

Figure 68. Cumulative exergy Fuel for waterflooding and polymer flooding.

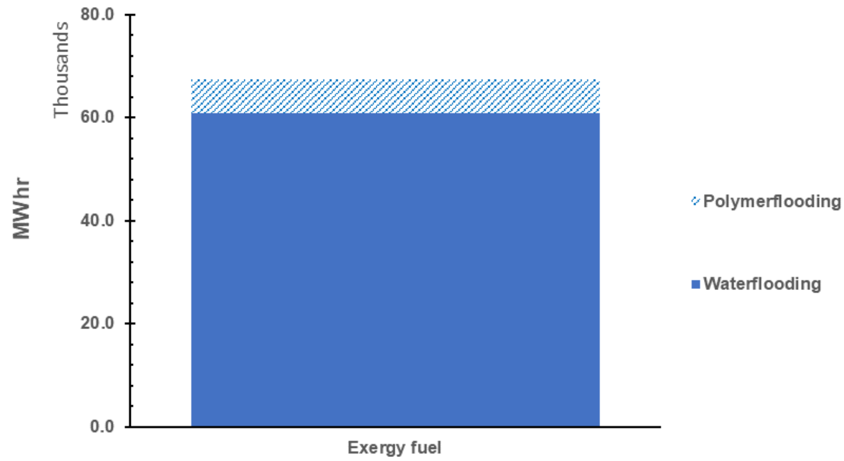

Figure 69. Additional exergy fuel invested at the end of year 20 for the polymer injection.

As the figure above shows, the difference in Exergy fuel invested is relatively low if compared to the amount of exergy destroyed in both techniques. When applying the polymer injection as much as additional 7 GWh need to be invested.

Just as seen with the oil production behavior, the polymer flooding technique allows to obtain more exergy product in comparison to the waterflooding technique. Figure 70 and Figure 71 show the behavior of the exergy product per year basis and the total additional exergy product recovered. Along the life of the technique, with the polymer injection, as much as 4,000 GWh of additional exergy product is recovered

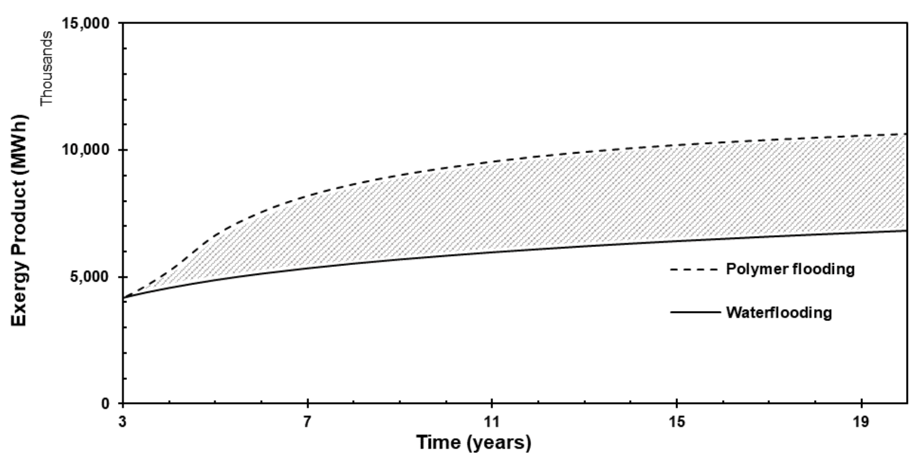

Figure 70. Cumulative Exergy product for waterflooding and polymer flooding.

Summarizing, even though the polymer flooding technique presents more Exergy destroyed and more Exergy needed as fuel, the increase in Exergy product is enough to make the technique more efficient overall. Again, as shown in Figure 64 the efficiency of the polymer injection decreases rapidly to a point where it is less efficient that the waterflooding. It is important to note that such results could be different given the reservoir responded less favorably to the treatment. It is for this reason that for every different application the analyses should be conducted thoroughly.

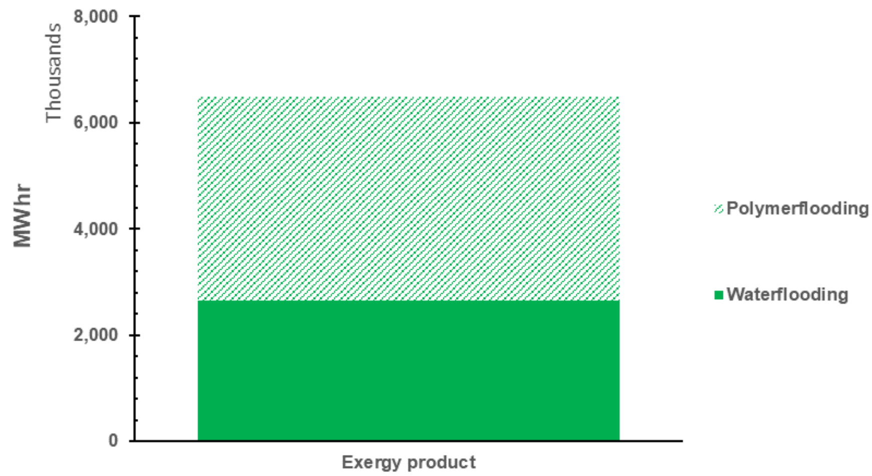

Figure 71. Additional exergy product when applying polymer flooding.

From equation (35) the exergy return on Investment is the ratio between the exergy recovered for society and the exergy invested as fuel. Figure 72 shows that the EROI at after year three a more efficient EROI results from improved efficiency due to higher exergy product recovered.

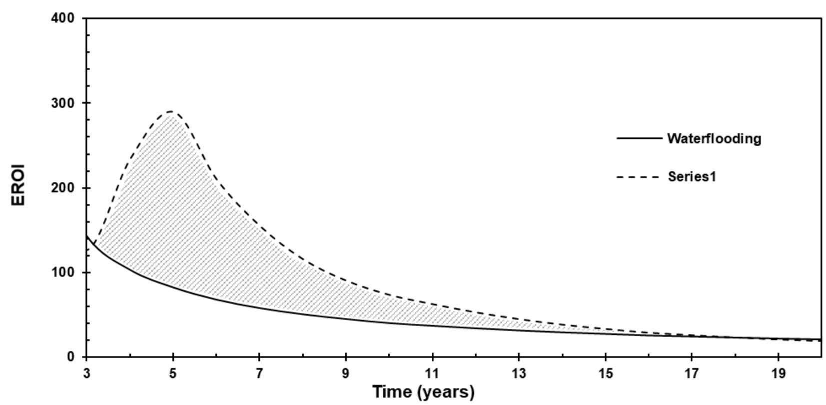

Figure 72. Exergy return on investment evolution along the years for both oil-recovery techniques.

After polymer injection commences at year three the polymer flooding keeps a higher EROI for the remaining of the technique life. It is noteworthy to mention that this ratio do not include the Exergy destroyed during the technique. Figure 73 shows that overall the polymer injection presents a better performing Exergy return on investment.

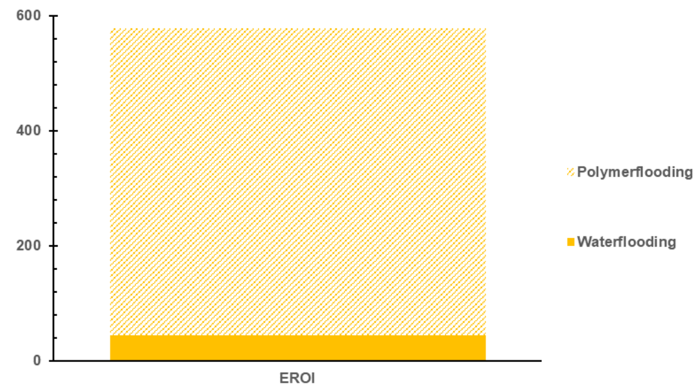

Figure 73. EROI for waterflooding and polymer injection.

Like the EROI the ExD/ExF ratio shows (Figure 74 and Figure 75) how much exergy is destroyed per unit of exergy invested as fuel. When the polymer injection commences, it shows a higher exergy destruction per unit of fuel in comparison to the waterflooding for the rest of the techniques life. This ratio shows that the polymer flooding is more intensive in exergy destroyed and could benefit more on efficiency upgrades than the waterflooding technique.

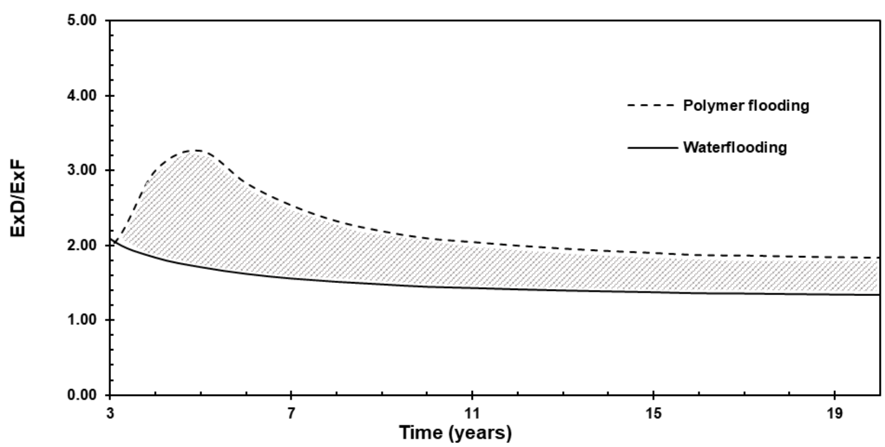

Figure 74. Exergy destroyed per exergy fuel invested along the years for waterflooding and polymer flooding.

While for the waterflooding base case the ExD/ExF ratio is 1.5, for the polymer injection it raises to 9.3 times more exergy destroyed than exergy fuel invested. This behavior results from a more fuel exergy intensive technique and due to the exergy destruction due to polymer disposal.

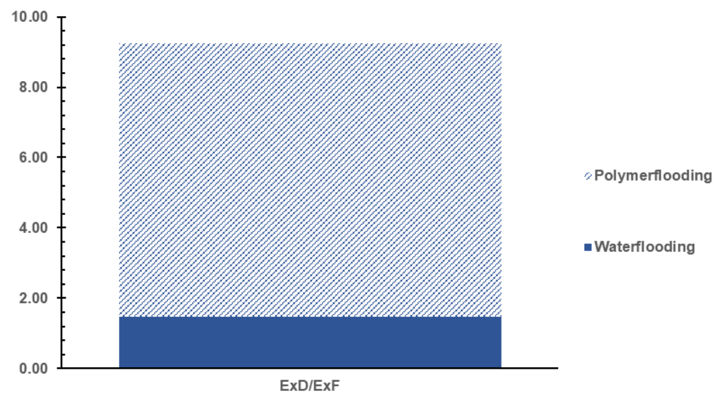

Figure 75. Exergy destroyed per Exergy Fuel ratio for waterflooding and polymer injection.

In an exergoeconomic analysis, the value of opex and capex is added as an hour cost rate to the costs incurred due to exergy invested as fuel and exergy destroyed. It can be seen that the cost per hour for an exergy unit of product is as much as 1.5 times higher for the polymer injection than for the waterflooding, from \$160/hr to \$250/hr. This results from higher initial investment and also higher opex along the life of the polymer flooding technique including also slightly higher fuel exergy and higher costed exergy destroyed. These behaviors are shown in Figure 76 and Figure 77.

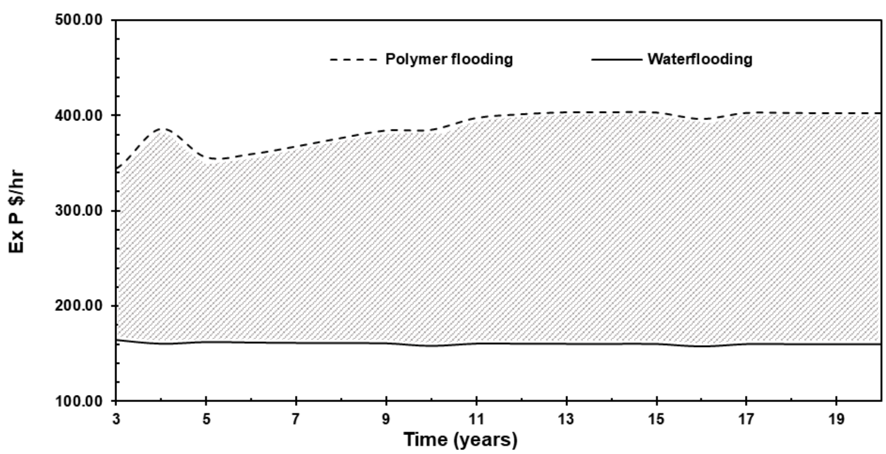

Figure 76. Increase in exergy product cost rate per hour along the years due to applying polymer injection.

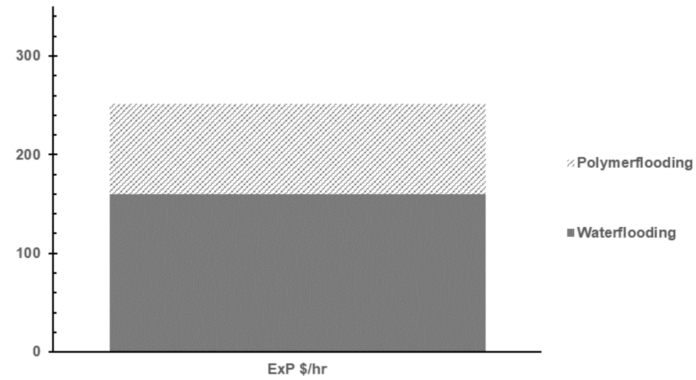

Figure 77. Increase in exergy cost rate per hour for the entire technique.

If the cost per MWh is considered instead of the hourly rate, it is also seen a high increase for the polymer injection technique, specially from year nine onwards (Figure 78 and Figure 79). At this point a declining oil production makes each equivalent MWh recovered more expensive. Considering the whole life of the technique, the cost per MWh increases $3.5 if polymer injection is pursued.

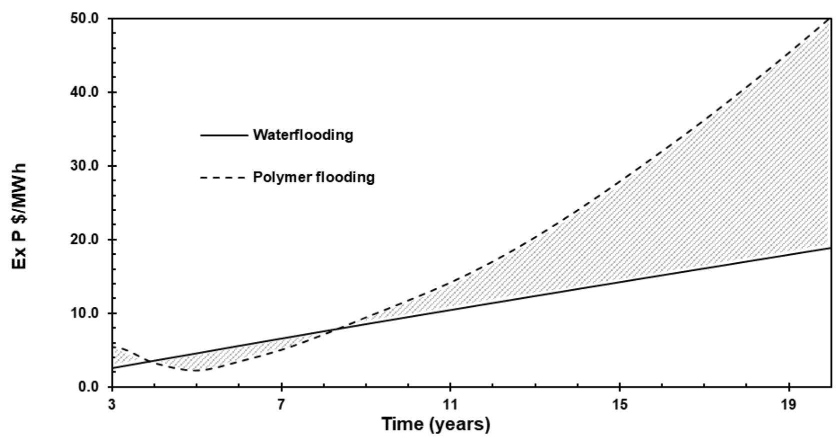

Figure 78. Increase in cost per MWh of exergy product per year due to polymer flooding.

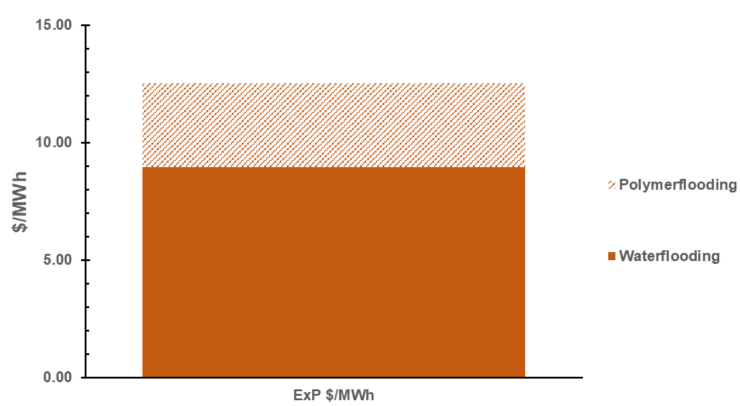

Figure 79. Cost per MWh of Exergy Product for both oil-recovery techniques.

To summarize the results of this analyses Table 19 shows the calculated values for both the waterflooding and polymer injection techniques. A brief description of performance for every parameter follows.

Table 19. Exergy results for Waterflooding and Polymer Injection.

Analysis	Waterflooding	Polymer Injection	Increase from base case
Exergy RF	94%	98%	4%
Exergy ROI	44	579	535
ExD/ExF	1.5	9.3	7.8
Ex P $/hour	160	252	92

The exergy recovery factor indicates how the net exergy (product minus its destruction and fuel) stands in comparison to the total exergy recovered as product. For this factor a higher value would mean a better performing technique.

Similarly, the exergy return on Investment tells the degree the exergy fuel compares to the total exergy recovered as product. A higher value indicates that for every exergy unit invested as fuel, more exergy is recovered as product.

In the case of the exergy destroyed by the exergy fuel ratio, a higher value would mean that the technique is less efficient and for every unit of exergy invested more exergy is destroyed. In this case a smaller value is preferred.

The cost rate for the exergy product gives an indication on the needed amount of money needed to recover a unit of exergy product. This cost rate includes investments and operating costs but also the costing from the exergy that is destroyed. A smaller value is preferred as it indicates that less money needs to be invested for the same amount of exergy product.

Only for the exergy destroyed and fuel ratio and the cost rate per hour of exergy product, does the waterflooding outperforms the polymer injection. Since the exergy destroyed and exergy fuel ratio does not account for the difference in exergy product, it is deemed not strong indication for preferring the waterflooding. In the case of the exergy product cost rate, it could be also an indicative that the technique may be more susceptible to the development of oil price in an economic sense.

It is considered then that the exergy and exergoeconomic analyses point to the polymer flooding as the preferred technique.

6.3. Real Options

For the real option comparison, the results obtained for the analytical and iterative RO analyzes are discussed.

Each technique showed a different optimal investment timing as a result of their value per barrel, profit per barrel and the payout rate δ. As can be seen in the figure below, the polymer flooding technique shows a lower optimal value for investment in relation to the waterflooding technique. If we analyze equations (45) and (48) we can conclude that this difference is mainly due to a higher expected payout rate for the polymer flooding. This payout rate in turn is influenced by the decline rate *w*, the profit per barrel *π* and the value per barrel *V*.

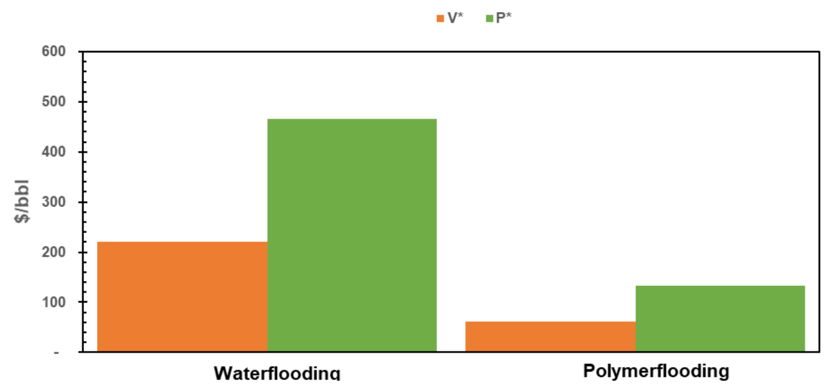

Figure 80. Optimal investment value V and optimal price P* for waterflooding and polymer injection.*

As shown in Figure 81 the expected value per barrel for both techniques is very similar along the years but their optimal value for the waterflooding is almost three times in comparison. Even when this analysis may hint that the better course of action for the polymer flooding is to wait until year 12, section 5.3 explains why the firm is better off exercising the option right away.

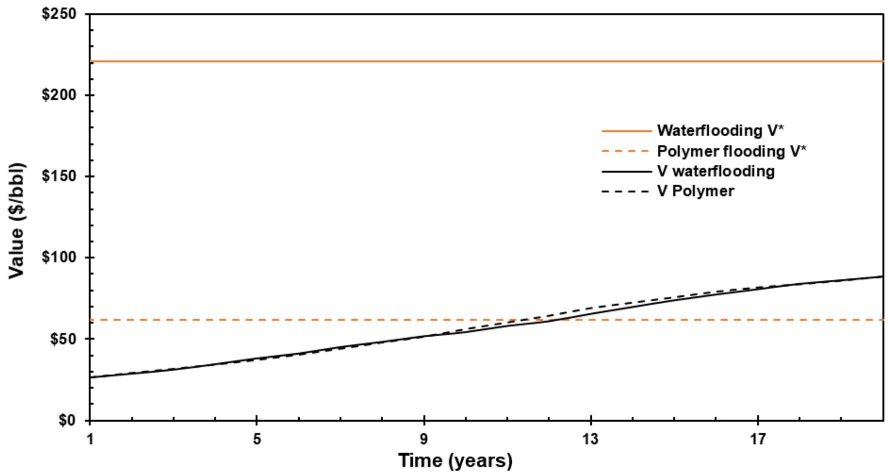

Figure 81. Value per barrel and optimal investment value for both oil-recovery techniques.

A lower optimal investment value means, from equation (48) and (46), that the firm could expect a better payout rate if the same risk free rate of return r_f and same standard deviation σ are considered.

Figure 82 shows that the value of exercising the option of applying the polymer injection technique remains higher than exercising the waterflooding technique along the years. The polymer flooding shows an analytic RO value of $75 million while for waterflooding a $65 million.

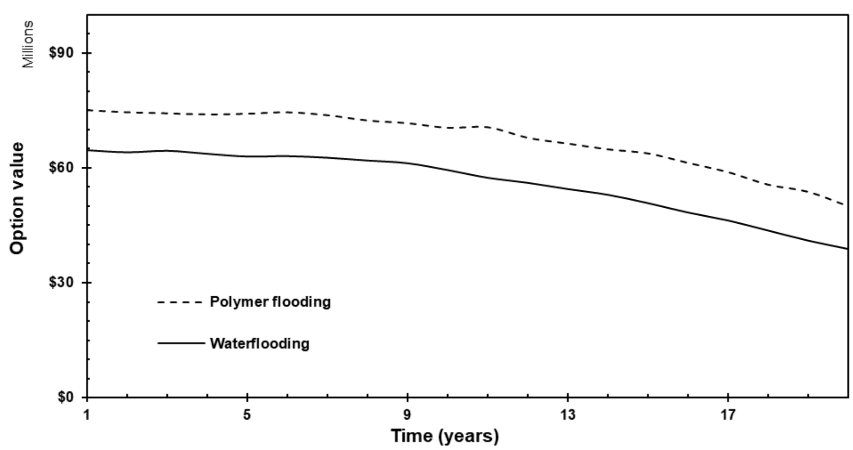

Figure 82. Option value for waterflooding and polymer flooding.

Figure 83 shows the additional option value if a polymer injection is followed instead of waterflooding is $10 million.

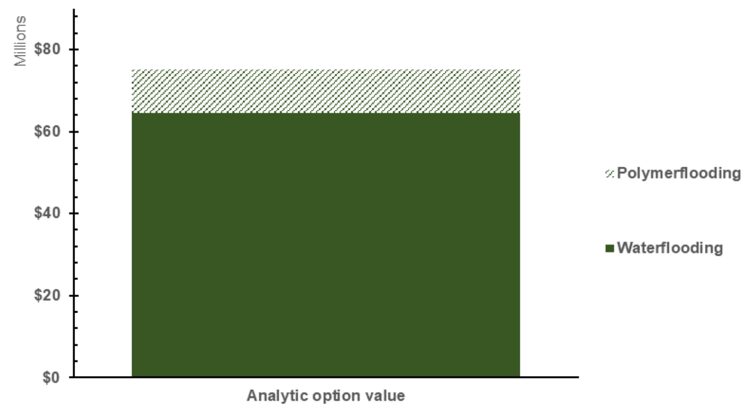

Figure 83. Incremental analytic option value if polymer flooding is applied.

For the iterative approach it can be seen in Figure 84 how also the polymer flooding presents a higher mean on the NPV cases distribution. It is also noteworthy to mention how the NPVs present a higher dispersion for the polymer injection. The reason has been pinpointed to its oil production behavior. If we go back to Figure 58 it can be seen how additional oil is produced after year three and onwards almost till the end of the technique life. This increased oil production will result on revenues with more uncertain oil-prices as uncertainty grows with time (Figure 33). For this reason, the NPV distribution is more spread in comparison to the waterflooding technique where most of its revenues come in the early years. This difference in dispersion can be linked to the level of confidence the results express. In a way there is more certainty on the option value given in the waterflooding than with the polymer injection technique.

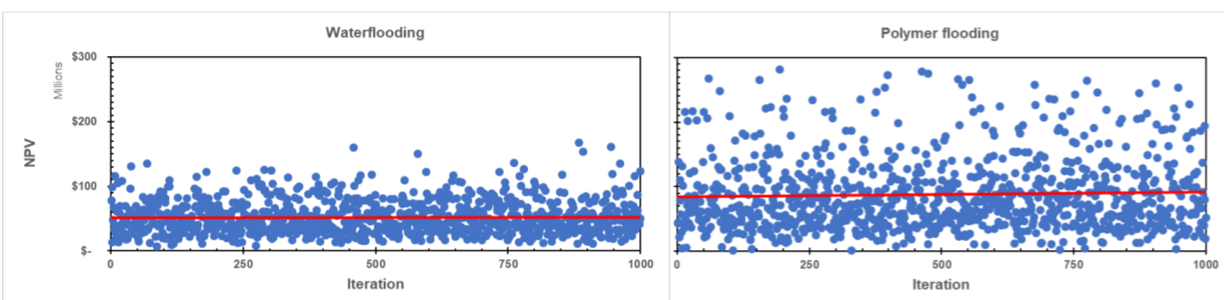

Figure 84. RO simulations for waterflooding and polymer injection.

Table 20 summarizes the iterative analysis for both techniques. The mean which represents the option value is greater for the Polymer flooding as well. If the percentiles are analyzed, for example the 10% percentile, we can see that similar values are found for both techniques, with slightly more favorable for the polymer flooding. The 10% percentile means that there is at least 90% probability to have an NPV case of at least $23 and $28 million for the waterflooding and polymer respectively.

Table 20. Iterative RO analysis comparison.

	Waterflooding (million)	Polymer flooding (million)
Mean	$51	$86
Median	$47	$76
Std deviation	$25	$54
Percentiles		
10%	$23	$28
25%	$32	$45

As mentioned in section 4.4, the simulated value of oil is capped at $500. After considering the oil price behavior by the IEA it was deemed that a price higher would represent an unrealistic value. This decision is a judgement call and the effect on the final results need to be discussed. It was found that if the oil price was left uncapped (reaching oil price values up to $1500 and more) the mean of the NPV distribution, would vary 2% ($1 million) from the capped value for the waterflooding. In the case of the polymer injection a variation of 3% ($3 million) was observed. The small effect can be traced to the notion that, while high oil price scenarios are present, the frequency of such cases is small in relation to less extreme scenarios. It can be argued that the difference is minimum and that the capping of oil price evolution has not meaningful effect in the results. It is important to remember that the results, despite coming from 1000 iterations, remain an interpretation of the uncertainty and the final values should not be considered as a definitive description of future results.

Figure 85 shows that for the iterative approach the incremental option value if the polymer flooding option is exercised is $35 million.

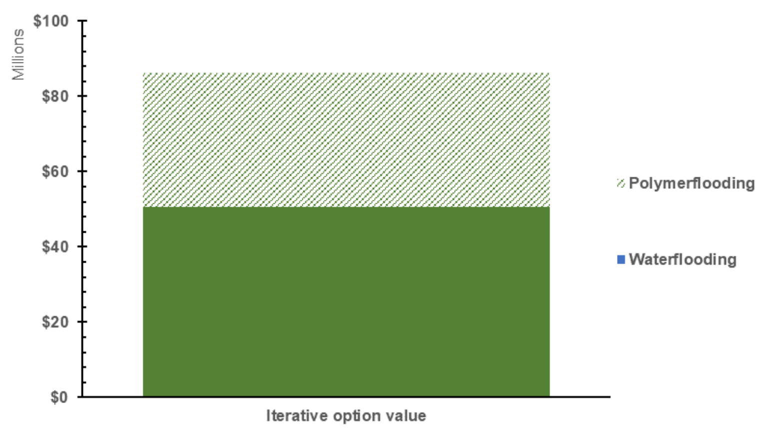

Figure 85. Iterative option value increment if polymer flooding option is exercised.

Table 21 summarizes the results for the analytic and iterative approach showing a more favorable forecast in both analyzes for the polymer flooding.

Table 21. Real option results for Waterflooding and Polymer Injection.

Analysis	Waterflooding (million)	Polymer Injection (million)	Incremental value (million)
Analytic RO	$65	$75	$10
Iterative RO	$51	$86	$30

6.4. Conclusion for the comparative analysis

After comparing the results with the proposed analyses, it was found that both the standard NPV and the RO theories would select the polymer flooding as best technique. Similarly, the Exergy and Exergoeconomic analyses select the polymer injection as preferred technique, even though, a less marked preference was found. The results per year show that at some point the polymer flooding can become less efficient that the waterflooding injection. Even though, overall, the polymer flooding still shows better exergetic efficiency.

7. Conclusions and recommendations

This final section discusses the relevance of this research and presents the main insights obtained. First, a reflections section is presented where the importance of the research undertaken in this thesis is analyzed through the lense of the management of technology program. Then, the conclusions for this thesis are provided, revisiting the research objective and research questions. Finally, recommendations are issued to other researchers in light of the results and the experience obtained while undertaking this research.

7.1. Reflections

7.1.1. Relevance of this research for the Management of Technology program

As Khalil and Ezzat (2001) argue, Management of Technology (MOT) is the discipline that brings together technology assessment and integration to business strategies. With an ever-changing environment it is important for strategies to adapt to such changes. The oil and gas industry is expected to play an important role in providing energy in the coming decades. Arscott (2003) recognizes that if the industry aims to follow a sustainable development, five main objectives should be followed: To meet the energy requirements in a cost-effective and safe fashion; to mitigate any environmental impact as a result of its activities; to collaborate with all sectors of society to promote sustainable development; to support communities where its activities take place and to keep a high ethical standard in all projects.

The concepts discussed in this thesis could influence the performance of a firm with respect to its sustainable development and economic performance. The current state of technique-selection based on the NPV rule can be argued to cover the first objective, but even then, the effect on market uncertainty is left unconsidered. Real Option theory can help to make better informed economic decisions in oil-recovery ventures. For the second and third objective, Exergy analysis can provide the needed information to improve the efficiency of the techniques and, likewise, to select more efficient ones over competing alternatives.

The analyses presented in this thesis have the potential to expand the assessment of technologies in oil-recovery projects from cashflow based screening methods to more inclusive ones. In order to link these assessments to business strategies, MOT discipline is of importance. As part of the MOT curriculum, decision-making is the study of the path of action selection among alternatives.

In the literature there exist several models to approach the decision-making process in an objective fashion (Pohekar, et al., 2003). Given that decision-making is complex in oil and gas projects, Multi-Criteria Decision Making (MCDM) models can be applied to consider NPVs and also exergy efficiency and risk adjusted cashflows.

The main contribution that this thesis can extend to managers is the notion that more criteria can be added to the selection of oil-recovery projects with the objective to tackle business environment shifts, like market uncertainties and growing environmental concerns. As society moves forward an energy transition, technology managers in the oil industry should consider that uncertainty in the markets will increase and that a more efficient performance will be demanded as the transition takes place.

7.1.2. Limitations on approach and discussion on theoretical choices

This study does presents limitations. Given the reduce number of techniques analyzed, no general conclusions can be draft with regards to the efficiency or profitability of the mentioned techniques. The work in this thesis aims to set a basis for the screening of more techniques and to describe the adaptations and considerations for applying real options and exergy analyses to oil-recovery techniques.

I now move to describe assumptions and limitations recognized will applying the analyzes to waterflooding and polymer injection oil-recovery techniques.

For the NPV rule the discount rate was obtained from the literature. As seen in the sensitivity analysis, the selection of a discount rate can affect the NPV results and is for that reason that special care should be taken in selecting it. Also, the oil-price is assumed to follow the scenarios proposed by the IEA. As mentioned in previous sections, the scenarios by the IEA include their own assumption that oil price is affected by the effect of new policy adoption on sustainability. I argue that oil price is influenced also by other forces such as supply and speculation. It would be advisable then, to base economic estimations on more thorough oil-price analyses. Additionally, capital expenses were partially estimated from information provided by the external advisor but the lack of additional information from other economic analyses did not allow to calculate the scale factor individually for each equipment. In real-life settings, this factor is easily calculated and should be done per equipment. Similarly, the operating expenses were calculated considering average values from the literature, including a single energy cost per kWh, which in real-life settings should be estimated considering changes in its costing as time passes.

For the Exergy analysis some technical aspects needed to be assumed or based on the literature due to lack of information. This analysis being more technical in nature can be performed with further detail in real-life applications. In the case of the oil-recovery simulations, assumptions are made on the injected fluid, such as all injections flows from the injection well to the production well, when in reality some fluid is lost to the formation. Furthermore, it is considered that no temperature transfer occurs after production before and after the heater. Nowadays the oil-recovery processes have sensors all along which can be used to calculate the exergy performance more realistically. For the chemical exergy of the polymer product, a theoretical exergy is calculated from the elements and the energy of formation needed to create the compound. This calculation can be considered an understatement of the exergy needed for the creation of the polymer, as it does not consider manufacturing and transportation processes. This limitation can be solved following a Life cycle approach of the needed materials.

In the case of the real-option analyses one of the most important limitations is the simulation of the oil-price. In this thesis a decision was made to cap the oil price development to a maximum of $500 per barrel. Greater values were deemed unrealistic based in part on the estimated performance by the IEA. While the most optimistic oil price by the IEA was $130, it was also deemed appropriate to allow greater values in the simulation to account for the possibility of even greater prices. It was analyzed what the effect of such assumption would have on the final option values if left uncapped. It was found that for the waterflooding only a variation of 2% was observed while a variation of 3% for the polymer injection. This results from the notion that, even though random paths with higher values do appear, such cases are by far less likely that with the values closer to the mean. Besides the approach followed in this thesis, oil-price following a browning motion process, there are other modelling approaches including mean reverting processes and mean reversion with jumps. And even the relative performance of this modelling methods remains debatable. Due to the complexity of dealing with future uncertainties, the only advise foreseeable to ameliorate this limitation is the use of more complex simulations like Agent Based Modelling (ABM).

An additional limitation is the way the analytic real-option approach describes the evolution of the option value along the years. In order to calculate an option value, the analytic approach assumes that the decline rate is constant along the years of the technique, while in real-life settings decline rates change every year. Similarly, the value per barrel is considered to be an average and constant but this will vary in reality as oil output is reduced and costs are spread among less production. One way to tackle this limitation would be to revisit the describing equation.

In the case of management relevance, the biggest obstacle for this expanded criterion to become common in the industry is the specific knowledge needed to carry the analyses. But, given that the oil and gas industry characterize itself for its high level of commitment in its personnel training, this obstacle can be overcome.

7.2. Conclusions

This thesis research starts by delineating the expected contribution of the oil and gas industry to meet the energy demand in the coming decades. After stablishing that fossil fuels are expected to play an important role, if current trends prevail, the selection of oil recovery techniques is discussed. Cashflow based methods are being used for the selection of alternatives which may overlook important parameters like efficiencies or market uncertainties.

Following, the research object of this thesis is the oil-recovery selection criteria. This type of projects is subject to market uncertainties and each alternative show specific technical consideration that may make them more or less efficient. With an ever-shifting economy, the uncertainty on oil-prices is high and selecting scenarios for economic appraisals is ever important as the final NPV is greatly affected by oil-price behaviors. Furthermore, with growing concerns on environmental topics, the oil and gas industry ought to include efficiency criteria to the selection of oil-recovery techniques. By analyzing the literature on how other industries have considered efficiencies and uncertainties in their evaluations, the present research explores the application of exergy and real option analyses on oil-recovery techniques.

Having in mind the aforementioned, the research objective of this thesis is to expand the economic evaluation of potential oil-recovery techniques alternatives by including efficiency performance (through exergy analysis) and uncertainty (through real option theory) in the decision-making process. Additional to the standard NPV rule, a waterflooding and a polymer injection oil-recovery technique are analyzed with exergy and real-options. The results obtained from these analyses point that the polymer injection is a more suited alternative. Theses analyses each have the potential to provide information for improvement of the techniques. The NPV analysis to distinguish the parameters that most affect the economy of the alternative. The exergy analysis to pinpoint the most inefficient piece of equipment in the whole process. And the real options to visualize the effect of oil-price uncertainties in the economics of the technique.

In order to fulfill the mentioned research objective, the following research sub-questions were used as a guide. I now move to revisit these questions and describe how the results obtained from this thesis answer them.

What are the considerations that need to be taken into account to apply exergy and real option analyses in oil-recovery techniques?

In order to answer this question, first, a literature review was conducted in order to learn how the analyses were applied to other industries and processes. Then the characteristics of waterflooding and polymer injection oil-recovery techniques were established.

For the exergy analysis, first, each piece of equipment need to be establish in the oil recovery process. For every equipment or energy carrier, it is important to establish its function and, the required energy that is invested into the equipment and what will the equipment effect be to the material streams. It is also needed to consider what compounds will be present in the material streams in order to calculate the exergy product and eventually the exergy that is destroyed. For the exergoeconomic analysis, it is important to have an exergy and economic analysis ready in order to link the exergy of the process to the related expenditures. Additionally, in order to cost the exergy fuel and the exergy destroyed a cost per exergy unit needs to be known.

For the real option analytic approach, the first step was to validate if the differential equation represented the option value of the oil-recovery techniques. Taking into account that differential equations are the representation of a value increase in relation to the increments of other variables, it was confirmed that the equations used considered the oil price change along the years, the risk adjusted rate of return, value per barrel after costs and the oil production decline profile, it was deemed a sufficient representation. It was then needed to define each of the mentioned parameters for the different oil recovery techniques. For the iterative approach the first consideration was to define the modeling of the oil price behavior. Then, for the Brownian motion it was needed to establish the standard deviation of oil price and the expected rate of change. Once the oil-price random walks are defined it is possible to calculate the NPVs just as in a standard economic analysis.

How can real option theory and exergy evaluation be used for screening oil-recovery techniques?

Once the results were obtained it was needed to establish a desired performance for each analysis. For the standard economic analysis, NPV is an indication of profitability after costs and thus a higher value is preferred. For this analysis the polymer injection technique showed a higher NPV even though it becomes uneconomic earlier.

In the case of the Exergy analysis four ratios were selected to reflect on the degree of efficiency of the studied oil-recovery techniques. The first ratio considered is the exergy recovery factor which is the proportion between net exergy (exergy product minus invested as fuel and minus exergy destroyed) and the exergy recovered as product. For this ratio a higher value means that less exergy is needed to be invested and less is destroyed in relation to the amount of exergy recovered as product. The polymer injection presented a higher exergy RF and was then preferred. The second ratio considered is the exergy return on investment which shows the proportion between the exergy invested as fuel and the exergy recovered as product from the recovery of fossil fuels. A higher value would be preferred as it would represent more exergy product is recovered for a unit of invested exergy. For this ratio, a high preference is observed for the polymer injection technique but attention must be given to the notion that in this ratio the exergy destroyed in the technique is leaved aside. For the exergy destroyed per exergy invested as fuel ratio (ExD/ExF) lower values is now the preferred state since it hints on how much exergy is destroyed per unit of invested exergy. In this case the waterflooding actually showed a better performance but it is to be noted that the relation of how much exergy is recovered as product is not considered.

Finally, for the real option analyses the screening parameter is the option value or the uncertainty adjusted NPV. Again, a higher option value will express a higher profitability in the presence of uncertainty. For both the analytic and iterative approaches the preferred technique is the polymer injection. One important aspect to consider is that with the iterative approach it is possible to analyze which technique shows a higher effect from uncertainty. Even when the polymer injection shows a higher option value, it does present a higher standard deviation in comparison to the waterflooding, indicating the technique is more affected by uncertainty.

How does the conclusions obtained as a result of conventional economic appraisals differ from those obtained when including efficiencies and uncertainty in the evaluation of enhanced oil-recovery techniques?

In this thesis the three analyses gravitated towards the polymer injection technique which would make the decision-making process straight forward. Even though, for other oil-recover techniques, or for other economic or technical conditions, it is possible that these analyses would yield different recommended alternatives. In this case, a recommended approach would be to make use of decision-making models like the multicriteria decision making (MCDM) (Pohekar, et al., 2003). Where the results of the analyses are given specific weights and an objective decision is made.

This sub-questions served as a guide to answer the main question:

How can real options and exergy analyses expand the cost-efficient selection of oil recovery techniques?

Throughout this thesis it has been explained the need to expand the screening criteria for the oil-recover techniques. Cashflow based screening allows to select the most profitable option from competing alternatives. Even though, important aspects are left aside like the efficiency of the techniques and the effect of uncertainty in market conditions.

The inclusion of exergy analysis can provide information on the efficiency of the techniques and by making this information accessible to managers it can promote the identification of inefficient processes and techniques. Similarly, the exergoeconomic analysis can provide a basis of comparison in monetary terms for the exergy destroyed and can facilitate the decision-making when considering equipment upgrades or modifications. It can also be argued that improving the efficiency of techniques can lead to better economic performance.

For the real-option results it gives a sense of the effect of uncertainty in the economics of the project. In this thesis, the assumptions made on the oil-price behavior point overall to an increasing oil-price along the years. As market conditions evolve, these assumptions can easily be adapted to represent current trends. Given the conditions presented in this thesis, the polymer injection technique presents a better valued option but it is also recognized that the effect of uncertainty affects this alternative more than the waterflooding. If the oil-price behavior in the future were to show low values it may even make the waterflooding technique to have a better option value as its economics are less affected by uncertainty.

Finally, it is important to sate the scientific and practical relevance of this thesis as part of the management of technology program.

The scientific contribution of this research is twofold: First, the exergy and exergoeconomic theories are applied to oil-recovery techniques where no similar approach has been found in the literature for these specific projects. Second, real-option theory, both analytic and iterative, are also brought to the specific characteristics of oil-recovery techniques. The use of existing theories to new applications are recognized as a form of scientific contributions as discussed by Verschuren et al. (2010).

The application of exergy, as shown in the literature review, has been applied to the downstream section of the oil industry value chain (refination of fossil fuels) but had not been applied for the upstream or extraction industry. Even though only two oil-recovery techniques are analyzed, the considerations and steps taken for these analyses can serve as a basis to study different oil-recover techniques or even processes in other industries.

For the aplication of real-options, the scientific contribution lies as well on the objective approach to adapt the theory for application in new settings. As different uncertainties are present in oil-recovery techniques, the analysis present in this thesis can serve as a basis to include additional sources of uncertainty. Similarly, it can serve as an example for the approach needed in order to apply real-option to processes in different industries.

What can also be considered as a contribution, is the notion of expanding the standard evaluation of competing alternatives from only cashflow based criterias. The practical relevance of this research is bringing the notion of more inclusive evaluation approaches to managers. Additionally, the information provided by this analyzes can provide managers the tools needed to improve the applied thecniques in both efficiencies and economic performance.

Exergy analysis has the potential to pimpoint the most inefficient part of a process, which in turn can allow managers to direct their resources for improvements. The exergoeconomic analysis can express a techniques exergy destruction intensity in less abstract terms. It can show the costs associated to this exergy destruction and in turn establish a comparison base with investment options.

The real-option theory allows managers to visualyze the effect of market performance in thier projects. These additional inteligence can allow better planning and resource allocation and even the timming of project execution. As further uncertainty sources are added, it can also provide with an understandy of the effects to real life projects.

7.3. Recommendations for research

The following recommendations are aimed to other researchers involved in the improvement of projects selection approaches, exergy analysis, market uncertainties modelling and oil-recovery methods design and evaluation. These recommendations are the results from the learnings obtained from the literature review, the adaptation of the analyses to the particular requirements from the oil-recovery techniques and from the evaluation of results and later discussion.

- To explore the applicability of the three studied analyses in more oil-recovery-techniques, in order to broaden the replicability robustness of their application.
- To explore the application of Exergy analysis with real field data on mass flow, temperature and pressure of the material streams and their respective chemical Exergy in oil-recovery techniques.
- To include more factors of uncertainty present in oil-recovery projects like energy costs, tax on CO_2 emissions and reservoir simulation uncertainty for the Real Option analyses.
- To analyze the applicability of the Analytic Real Options as a preliminary screening tool where initial info is limited.
- To analyze the use of multi-criteria decision making as a model to include exergy and real options in the selection of oil-recovery techniques.

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