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Future-Oriented Policy Making in Oil Exploration and Extraction Using a System Dynamics Approach

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ABSTRACT

Over the years, the process of studying, exploring, and extracting oil has undergone numerous transformations. On the one hand, the limitations arising from the depletion of oil reserves and the increasing global demand for this valuable commodity, and on the other hand, the growing dependence of industries on fossil fuels, lack of integration in optimal consumption patterns, labor strikes in the oil sector, wars, and political unrest, and instability in the oil market have led major oil-producing countries to implement a wide range of policies to achieve optimal conditions for oil exploration, extraction, and consumption. Moreover, global concerns about the depletion of strategic oil reserves and worries about achieving sustainable and lasting security in the supply of this product make it imperative to seriously address policy-making in the field of exploration and supply. This paper attempts to study the past and present trends of oil exploration and extraction, examine the main and root causes influencing this process through a system dynamics model, and conduct a content analysis on the best policy-making approach for oil exploration and extraction. The Vensim PLE 7.3.5 software was used to analyze the model components.

Keywords

System dynamics, Non-renewable resource management, Oil exploration and extraction, Future-oriented policy making, Causal loop diagram.

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1. Introduction

Oil was first discovered in August 1859 in Pennsylvania, United States. Within less than a decade, its production skyrocketed from 500,000 barrels per year to 5 million barrels per year. By 1890, this figure had reached 50 million barrels per year, and in 1922, production soared to about 500 million barrels per year. This increase continued until the early 1980s. From the mid-1980s onward, total production gradually decreased (Table 1), following a cyclical pattern due to the depletion of known oil reserves and the need to search for new sources (Hao, 2023).

Table 1. Top oil producers, exporters, consumers and importers in the world in 2023 (Million barrels per day)

Producers	Production volume	Importers	Import volume	Consumers	Consumption volume	Exporters	Export volume
America	12.9	china	10.6	America	19.6	Arabia	7.4
Russia	10.1	America	6.1	China	15.8	Russia	4.8
Arabia	9.7	India	4.7	India	5.3	Iraq	3.7
Canada	4.6	Japan	3.4	Japan	3.7	America	3.6
Iraq	4.3	South Korea	0.3	Russia	3.5	Canada	3.4
China	4.2	Germany	0.2	South Korea	2.8	United Arab Emirates	2.7
Iran	3.6	Netherlands	1.7	Arabia	2.6	Kuwait	1.9
Brazil	3.4	Italy	1.3	Canada	2.5	Norway	1.6
United Arab Emirates	3.4	France	1.2	Brazil	2.4	Nigeria	1.4
Kuwait	2.7	Spain	1.1	Germany	2.3	Kazakhstan	1.3

Therefore, as discovered resources became depleted, it became imperative to explore new sources because existing resources could not meet the growing demand. Moreover, oil imports alone could not satisfy the generated demand for oil in countries such as the United States. Furthermore, countless resources remained undiscovered, potentially containing substantial amounts of oil. However, discovering new resources required substantial expenditure and the utilization of numerous facilities. Since oil is a non-renewable resource, it should be used in high-value-added industries such as petrochemicals and similar applications. Additionally, it became necessary to search for new energy sources other than fossil fuels like oil to make the best use of the available oil reserves.

Based on forecasts made by the International Energy Agency, until 2025, crude oil will continue to play the main role in meeting the world's energy needs. It will supply 39 percent of the world's energy in 2025. Notably, according to forecasts made in different scenarios, the share of the Persian Gulf region from the total world crude oil production in 2045 will reach 55 percent in the maximum crude oil price increase scenario and 75 percent in the minimum crude oil price increase scenario. Therefore, providing effective solutions to ensure the security of crude oil supply and production and reduce its vulnerability to unforeseen factors will be of great importance for the countries of the region, including the Islamic Republic of Iran (Sulaiman et al., 2024).

1.1. Future-oriented policy making

Future-oriented policymaking refers to a process in which decision-makers and policymakers actively and consciously try to formulate plans, strategies, and policies that not only address current needs and challenges but also Prepare for possible future developments and challenges. This type of policy is particularly important for several reasons and includes various principles and methods. Reasons for the importance of Future-Oriented Policy Making:

- Anticipating rapid and complex changes: In today's world, technological, economic, social, and environmental changes are occurring rapidly. Future-Oriented Policy Making helps governments and organizations adapt to these changes and take advantage of new opportunities.
- Risk management and uncertainty: Due to the uncertainties in the future, Future-Oriented Policy Making helps to identify and manage possible risks and challenges.
- Sustainability and long-term development: Future-Oriented Policy Making focuses on sustainable and long-term development in such a way that resources and the environment are preserved for future generations.

1.2. Principles of future-oriented policy making

(1) Foresight: using foresight tools and methods such as scenario planning, trend analysis, and forecasting to identify possible future changes and challenges.

(2) Flexibility: Creating flexible policies and strategies that can quickly adapt to changes and new conditions.

(3) Participation and Collaboration: Encouraging broad participation and cooperation from various stakeholders including the public, private, civil society, and the general public to gather diverse views and information, making everyone feel valued and integral.

(4) Integration: coordination and integration between different policies and programs in order to avoid contradictions and strengthen efficiency and effectiveness.

(5) Sustainability: Focusing on sustainable development and preserving resources for future generations in all policy dimensions.

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1.3. Future-oriented policy methods and tools

(6) Scenario Planning: Designing and analyzing different scenarios to better understand possible future paths and prepare for each of them.

(7) Trend Analysis: This method is crucial for identifying and investigating macro trends and their effects on the future. It is a key part of strategic planning that can help businesses adapt to changing market conditions

(8) SWOT Analysis: This evaluation of strengths, weaknesses, opportunities and threats related to policies and strategies is a fundamental part of strategic planning. It's a comprehensive tool that can guide decision-making and strategy development.

(9) Strategic Mapping: drawing strategic maps to identify the paths to achieve long-term goals.

(10) Surveys and Public Consultations: Use surveys and public consultations to gather broad stakeholder information and views.

(11) Policy Making using System Dynamics: System dynamics offers a framework to model and simulate complex systems. It allows us to see the bigger picture and visualize the outcomes of various policy scenarios, taking into account various factors and their interdependencies.

1.4. System dynamics

In recent years, system dynamics has been used as an effective technique in the analysis and development of resources (Lee et al., 2023). This technique was developed by Forrester and is presented as a problem-solving approach for complex issues with an emphasis on structural aspects (Forrester, 1997).

Systems are defined and modeled based on causal relationships. The models include the following variables (Camps-Valls, 2023):

(1) State variable, which shows the state of the system,

(2) Rate variable, which shows the rate of change of state variables at any given time,

(3) Auxiliary variables, which explain the relationships in the model and make it understandable.

System dynamics was initially used as a methodology to study industrial management issues and has since been used to analyze social systems such as population control mechanisms and food supply (Meadows, 2004; Madadyniaa et al., 2024). System dynamics plays an important role in understanding the long-term mutual effects of a system. This approach has been applied to many issues such as financial planning, solid waste management (Rafew and Rafizul, 2023; Ng and Yang, 2023), forecasting the state of greenhouse gases in the world, supply chain management, transportation management, and technology policy analysis (Camps-Valls, 2023). In the energy sector, this approach was first used in the United States for gas supply. Its research focused on the long-term effects of demand growth, resource depletion, price, and financial and environmental constraints for the development of new resources (Karbasioun et al., 2023). In this paper, an attempt has been made to develop a dynamic model for oil resources to examine various policies in the field of oil exploration and extraction, as well as the depletion of oil resources along with growing demand.

2. Literature review

Several studies have been conducted in the field of oil exploration and extraction using dynamic systems. A system dynamics model was presented by Kiani and Pourfakhraei (2010), which considers the feedback between supply and demand and oil revenue of the existing system in Iran, considering different sectors of the economy. By using a systems approach, Hosseini et al. (2016) developed a conceptual framework to demonstrate various (economic and financial, technological, political, demographic, and industrial) factors that impact the dynamics of the futures and spot prices with their interrelations. Espinoza et al. (2019) developed Hubbert-based models to project future oil extraction in Ecuador. Hendalianpour et al. (2022) designed a system dynamics model to simulate criteria affecting oil and gas development contracts. Raj et al. (2023) investigated a system dynamics approach to evaluate the oil and gas supply chain. The review of the literature shows that hardly any studies have been done in the field of futuristic policy in oil exploration and extraction using the system dynamics approach. As a result, this field will be examined further.

In addition, Jenkins et al. (2011), in their book entitled Cost-Benefit Analysis for Investment Decisions" used the economic evaluation of oil exploration projects according to the approach of cost-benefit ratios. Robinson and Scott (2016) published their research in the field of oil exploration with a strategic planning approach in the book "Strategic Planning for the Oil and Gas Industry" has published. O'Sullivan and O'Sullivan (2016), in the article "Reservoir Modeling and Simulation: A Case Study" examined the modeling and management of oil resources through simulation in a case study reservoir. AL-Mahasneh (2017), in the article "Optimization of drilling operations in oil and gas wells" has optimized oil exploration and extraction operations through numerical modeling. Lisitsa (2019), in her article entitled "Supply-chain Management in the Oil Industry" studied the optimization of oil extraction supply and logistics processes in order to reduce costs and increase efficiency with the approach of supply chain management. Ponomarenko et al. (2022), in their book entitled "Economic Evaluation of Oil and Gas Projects" analyzed oil projects in the field of oil exploration and extraction through the management of technical, financial, and environmental risks.

Although each of the above researches examined a special aspect of oil exploration and extraction, due to the static nature and structural limitations of the future-oriented policy, most of them are unable to correctly predict the future situation, especially when combining different scenarios. Based on this, current research tries to increase decision-makers predictive power by correctly understanding this issue and using the capacity of dynamic system simulation, especially in the combined use of effective variables in future-oriented policies and paying attention to their dynamics.

This issue is considered an outstanding feature and innovation for managers and decision-makers in the oil industry management and planning field.

3. A system dynamics model

Oil, as a pivotal capital resource, is a cornerstone of the economic development of countries. However, the global limitation of oil resources, combined with escalating production and consumption, is leading to a decline in proven oil reserves. This, in turn, is driving up the cost of this precious material , including production and exploration costs. Therefore, in light of the oil market fluctuations, the changing energy landscape, evolving consumption patterns, and the diminishing proven oil resources, it is crucial for countries to develop targeted policies. These policies should address key factors influencing the industry, such as exploration, extraction, production, consumption, export, import, and the promotion of alternative energies. It is obvious that, due to the dynamic nature of the components and the complexity and diversity of the influencing factors, the dynamic system approach is considered one of the best policy methods in this field.

It should be noted that the adoption of ineffective policies based on trial and error, in addition to imposing a lot of costs on countries, caused a crisis in this industry due to the mismatch of effective components, which has adverse economic and social consequences.

It should be noted that the adoption of ineffective policies based on trial and error, in addition to imposing a lot of costs on countries, has caused a crisis in this industry due to the mismatch of effective components, which has adverse economic and social consequences.

Given the complexity of the behavior of a non-renewable energy resource system, the behavior of the non-renewable energy system is examined under a system dynamics model in order to investigate the mutual effects of influential factors, such as the volume of existing reserves, exploration costs, total costs, investment in exploration, price demand, usage rate, sales revenue, discovered reserves, and extraction costs (Lerche, 2004). This model analyses the necessary policies to achieve a set of long-term goals for the optimal use of crude oil.

3.1. Model components

Since non-renewable resources such as oil, coal, and natural gas are limited, they require comprehensive planning and precise development. To make more effective use of these resources, it is necessary to consider the long-term results of current efforts. Therefore, decisions must be made based on long-term analyses to ensure that relevant considerations are applied in all aspects. Figure 1 shows the causal loop diagram of the related model.

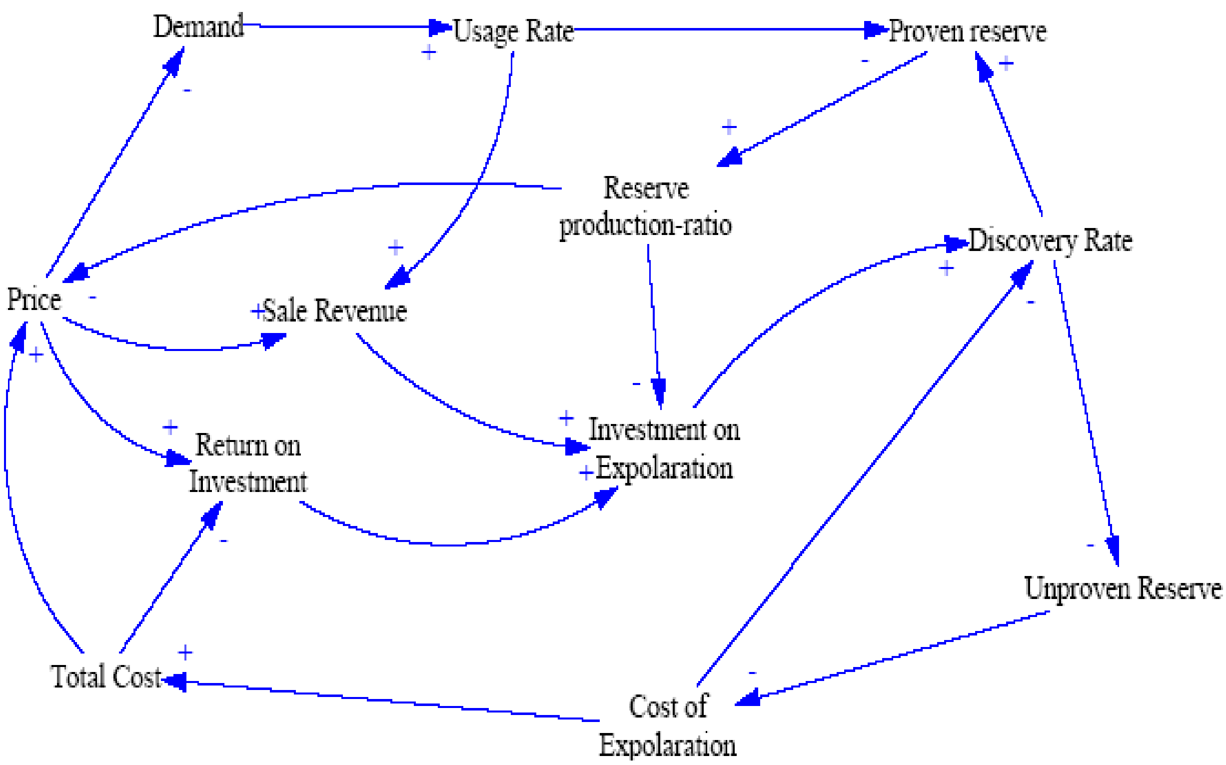

Figure 1. Causal loop diagram of the model

According to the above diagram, two important state variables can be identified: first, the Proven Reserve, and second, the Unproven Reserve. As the amount of undiscovered resources decreases, the exploration cost increases because the search must focus on inaccessible and difficult areas (Adelman, 2002; Sasraku, 2016). On the other hand, fewer resources will be available over time. Therefore, an increase in exploration costs will lead to a decrease in the discovery rate, resulting in a slower decrease in the amount of undiscovered resources.

Additionally, an increase in exploration costs will lead to an increase in total costs, which will consequently result in a decrease in the Return on Investment. An increase in the production rate decreases the Reserve-Production Ratio, and an increase in the Proven Reserve leads to an increase in the Reserve-Production Ratio.

On the other hand, a decrease in price will lead to an increase in demand, which in turn will cause the consumption rate to rise and, consequently, an increase in sales. It will naturally lead to an increase in investment in exploration until the Reserve-Production Ratio reaches the Desired Reserve-Production Ratio (Peng and Luo, 2022). Figure 2 shows the flow diagram of the model on which the simulation will be based.

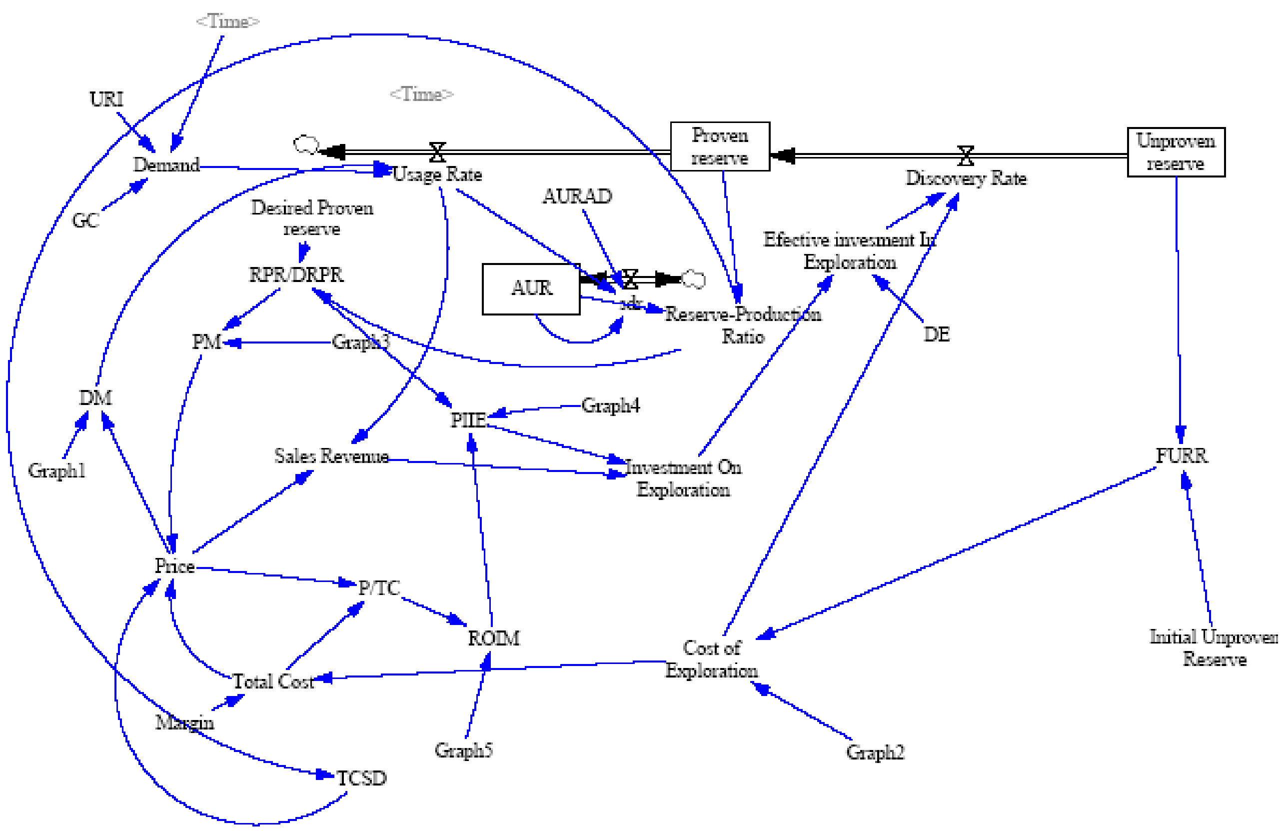

Figure 2. Flow diagram of the model

3.2. Auxiliary variables

The first auxiliary variable used in the model is FURR, which is the ratio of undiscovered reserves to the initial undiscovered reserves at any given time. Figure 3 shows the graph related to the Cost of Exploration as a function of FURR.

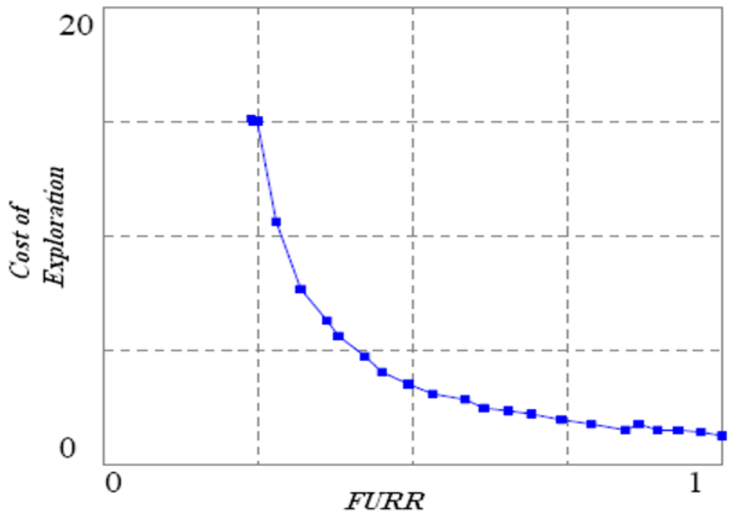

Figure 3. Cost of exploration versus FURR

As evident from the figure, as FURR decreases, the Cost of Exploration increases. The term "Reserve-Production Ratio" represents the ratio of Proven Reserves to the Average Usage Rate (AUR), indicating how long the discovered resources will last at the current consumption rate. Additionally, the Total Cost affects the Price through a third-order delay function (Adelman, 2002). Furthermore, to calculate the Total Cost, the Margin coefficient, which essentially converts the Cost of Exploration into the Total Cost, must be multiplied by the Cost of Exploration. The Price Multiplier (PM) indicates the producer's response to changes in the Reserve-Production Ratio (Figure 4).

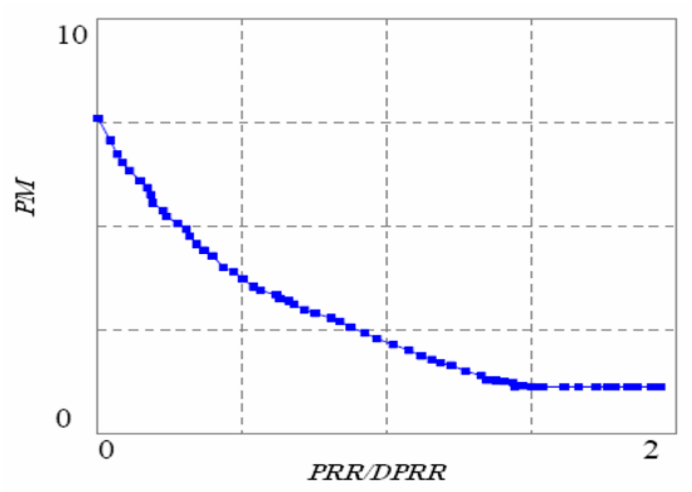

Figure 4. Price multiplier versus PRR/DPRR

From Figure 4, it has been observed that as the Reserve-Production Ratio increases, the Price Multiplier (PM) decreases. This is because the number of years for which the discovered reserves can be used exceeds the expected years of use. Consequently, the price decreases.

Therefore, when the Usage Rate increases, the Reserve-Production Ratio decreases, and the price at which the producer is willing to supply increases. Another logical assumption, derived from statistical analysis of consumption results in developed countries like the United States, shows that the growth in oil demand follows an exponential function with a 7 percent growth (Sasraku, 2016). However, these percentages may be revised in some regions to implement different policies. The Demand Multiplier (DM) represents the consumers' response to price changes. In fact, the consumers' response to price increases is negative (decreasing).

The sales revenue is determined by multiplying the price by the usage rate. Similarly, the Return-On-Investment Multiplier (ROIM) is obtained based on the ratio of Price to Total Cost (P/TC) through the graph given in Figure 5. When the average price is lower than the total cost, the investor decreases their investment, and when the ratio of the average price to the total cost (P/TC) is greater than 1, the producer increases their investment in exploration.

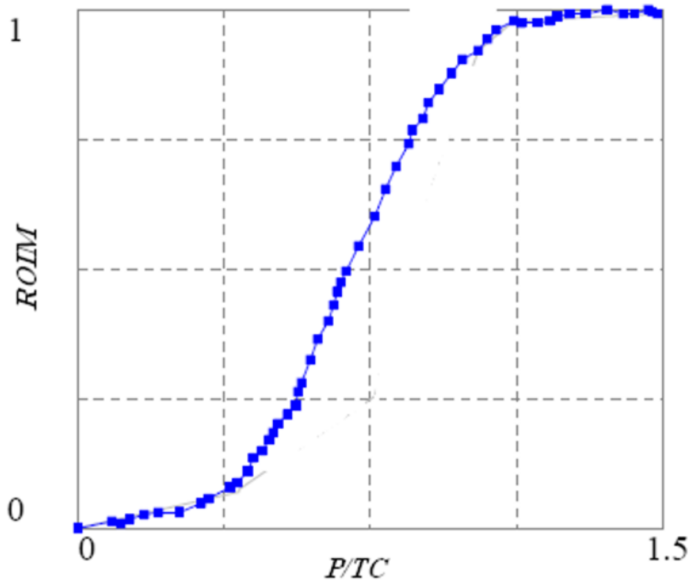

Figure 5. Return on investment multiplier versus P/TC ratio

The percentage of revenue invested is not only a function of ROIM but also a function of PRR/DPRR. When the PRR/DPRR ratio is less than 1, the investor decreases their investment, and when the PRR/DPRR ratio is greater than 1, the investor increases their investment. Figure 6 shows the percentage of revenue invested in exploration as a function of the PRR/DPRR ratio.

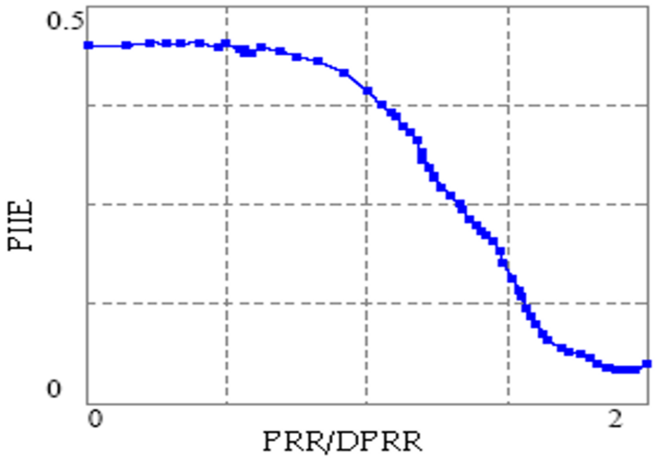

Figure 6. Percentage of investment in exploration versus PRR/DPRR

Investment in exploration is equal to the product of sales revenue and the percentage of revenue invested in exploration (PIIE). Investment in exploration affects the effective investment in exploration based on a third-order delay function. This third-order delay is such that the result of investment in exploration, due to the time delay caused by finding a suitable location for drilling, drilling the well, and accurately estimating the size of the discovery, cannot be accounted for in the first 4 to 5 years.

The percentage of revenue invested in exploration (PIIE) is expressed as a function of PRR/DPRR. As PRR increases, the percentage of investment in exploration decreases, and as PRR decreases, the percentage of investment in exploration increases (Lerche, 2004).

The formulas and types of each variable are mentioned in Table 2. As a result of running the model with the initial values given in Table 2, the following results are obtained.

Table 2. Initial values and model formulation

Variable	Type	Formulation
Unproven reverse	State	"Discovery Rate"
Proven reserve	State	"Discovery Rate-Usage Rate"
FURR	Auxiliaries	"Unproven reverse/Initial Unproven Reserve"
Initial Unproven Reverse	Auxiliaries	4.00E+11
Cost of Exploration	Auxiliaries	Graph2(FURR)
Discovery Rate	Rate	Effective investment In Exploration/Cost of Exploration
Total Cost	Auxiliaries	Cost of Exploration*Margin
Margin	Constant	3.7
ROIM	Auxiliaries	Graph5("P/TC")
P/TC	Auxiliaries	Price/Total Cost
Price	Auxiliaries	PM*SMOOTH(Total Cost, TCSD)

Variable	Type	Formulation
TCDSD	Auxiliaries	Reserve-Production Ratio
Sales Revenue	Auxiliaries	Price*Usage Rate
Investment on Exploration	Auxiliaries	PIIE*Sales Revenue
Effective investment In Exploration	Auxiliaries	DELAY3(Investment on Exploration, DE)
PIIE	Auxiliaries	Graph4("RPR/DRPR")*ROIM
PM	Auxiliaries	Graph3("RPR/DRPR")
RPR/DRPR	Auxiliaries	Reserve-Production Ratio/Desired Proven reserve
Desired Proven reserve Ratio	Constant	7
Reverse-Production Ratio	Auxiliaries	Proven reserve/AUR
DM	Auxiliaries	Graph1(Price)
Usage Rate	Rate	MIN(Proven reserve , Demand*DM)
AUR	State	Sdr
sdr	Rate	(Usage Rate-AUR)/AURAD
UR1	Constant	5.45E+09
URI	Constant	9.23E+07
UR1	Constant	
GC	Constant	0.07
GC1	Constant	0.07
DE	Constant	4.5
Demand	Auxiliaries	URI*EXP(GC*(Time-1900))
AURAD	Auxiliaries	1
Graph1	Look Up	
Graph2	Look Up	
Graph3	Look Up	
Graph4	Look Up	
Graph5	Look Up	

Figure 7 shows that with the initial values considered for the parameters and state variables, the demand increases by 7% per year, and accordingly, the undiscovered reserves decrease. This decrease was not very noticeable until the year 2000, but after that, it became significant, reaching zero by 2040. Additionally, the discovered reserves increase until they reach their maximum value in 2040 and then decrease until they reach zero. The potential demand growth, as shown in Figure 7, increases exponentially.

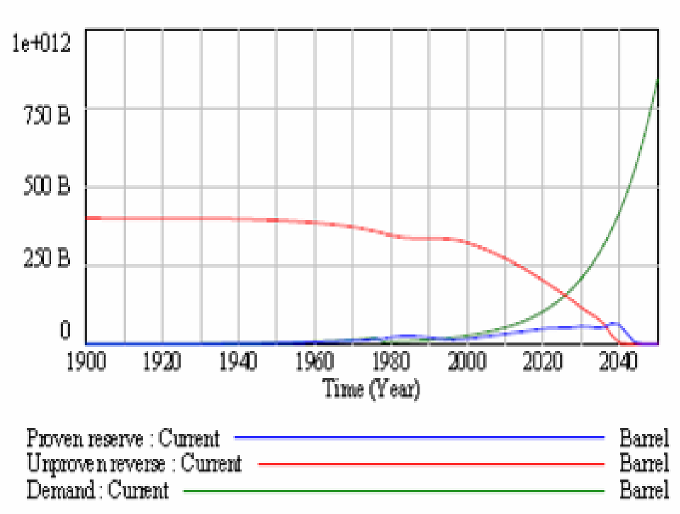

Figure 7. Model results based on Table 2 assumptions

From Figure 8, it can be seen that the cost of oil exploration remains approximately constant until 2020 because the undiscovered resources have not changed significantly. After that, the cost of exploration increases sharply. Consequently, since the price is entirely dependent on the cost of exploration, the conditions related to it are similar to those for the cost of exploration. Regarding the sales rate, it is observed that the sales increase until 2040 and decrease after 2040 due to the depletion of discovered reserves, gradually approaching zero.

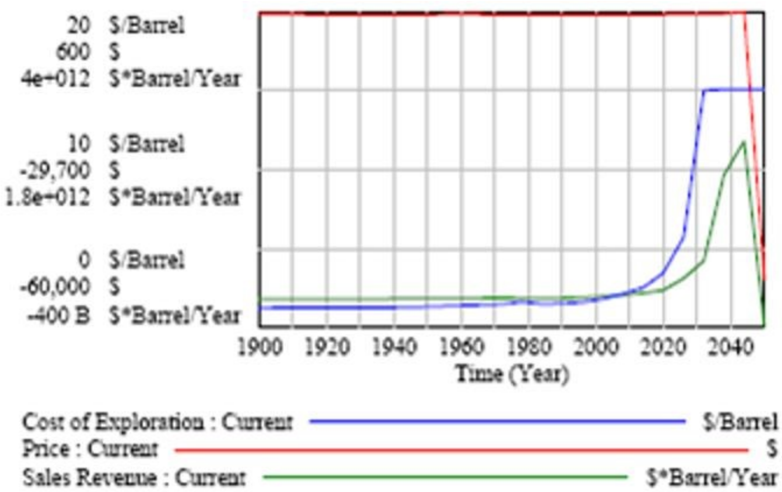

Figure 8. Some other model variables based on Table 2 assumptions

As can be observed from Figure 9, the effective investment is increasing until it reaches its maximum value in 2045. After that, due to the depletion of undiscovered reserves and the consequent decrease in sales, the investment decreases. As a result, this will also lead to a decrease in effective investment. Regarding the discovery rate, an upward trend was initially observed until 1978, when it decreased due to a decrease in investment caused by an increase in the PRR/DPRR ratio. Investment in exploration follows a similar pattern that is discussed in the analysis of effective investment.

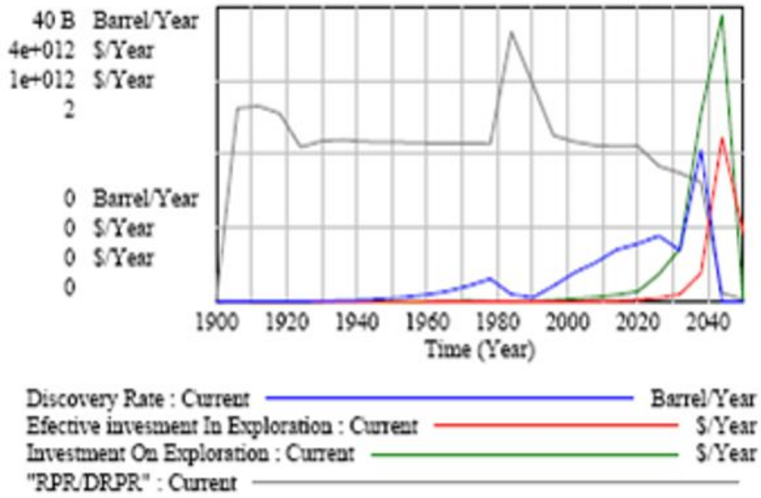

Figure 9. Analysis of some other model variables based on Table 2 assumptions

4. Model sensitivity analysis

In order to analyze the sensitivity of the model, the initial value of the Unproven Reserve variable has been decreased from 400 trillion to 300 trillion. Figure 10 shows the Unproven Reserve, Proven Reserve, and Demand variables. The Unproven Reserve variable starts decreasing earlier than before and reaches depletion about ten years earlier.

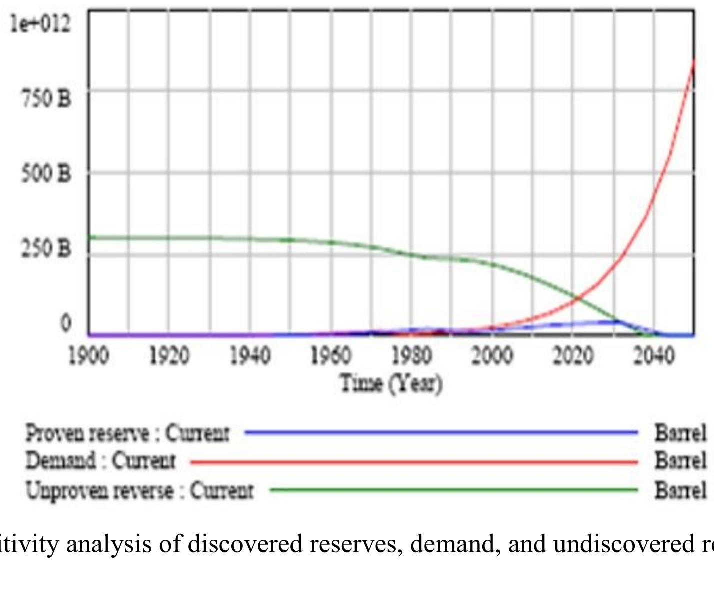

Figure 10. Sensitivity analysis of discovered reserves, demand, and undiscovered reserves variables

The sensitivity of the behavior of the Cost of Exploration, Price, and Sales Revenue variables has been analyzed. This analysis shows that these variables will exhibit behavior similar to the previous case (Figure 11).

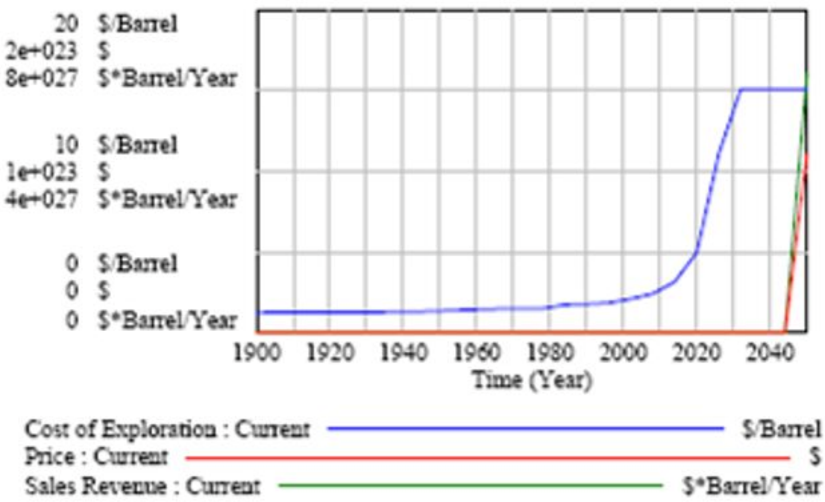

Figure 11. Sensitivity analysis of exploration cost, price, and sales revenue variables

In Figure 12, the Discovery Rate, Effective Investment in Exploration, Investment in Exploration, and RPR/DRPR variables are subjected to sensitivity analysis. Here, too, it can be observed that the variables' behavior does not differ significantly from the previous case.

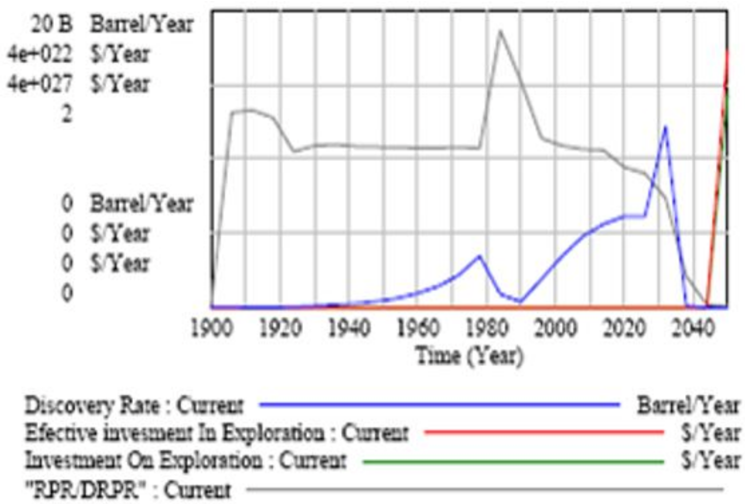

Figure 12. Sensitivity analysis of discovery rate, effective investment in exploration, investment in exploration, and RPR/DRPR ratio variables

Now, to implement other policies, the potential demand decreased from 7% to 2% starting from 1978. Figure 13 shows that by decreasing the demand growth rate, the utilization of reserves decreases, which will result in better utilization of the reserves and their depletion at a later time.

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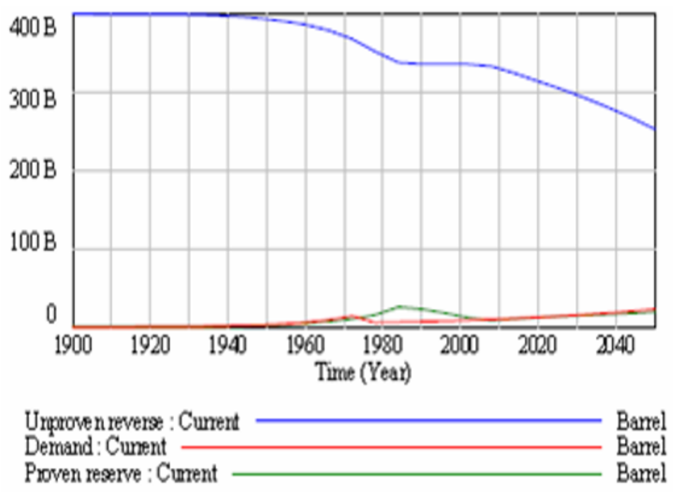

Figure 13. Variable behavior with implementation of new policy

Figure 14 shows the behavior of variables such as exploration cost, price, and sales revenue under the new scenario. It is noteworthy that despite the fluctuations observed in these variables, they ultimately increase in an upward trend.

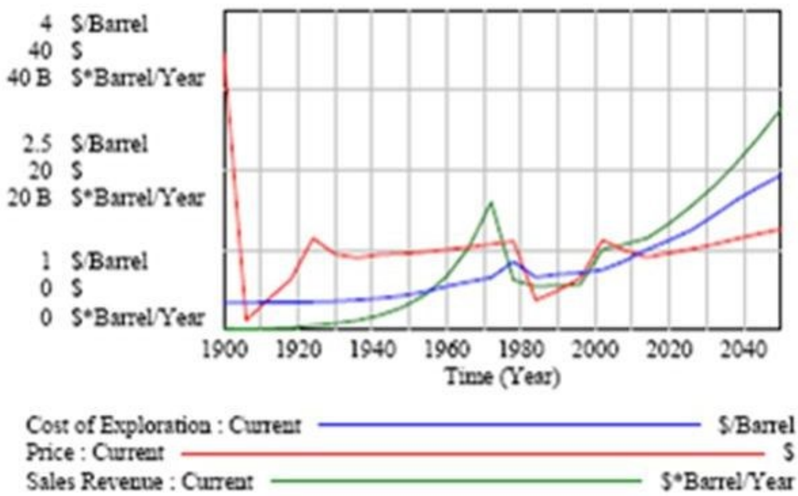

Figure 14. Variable behavior with implementation of new policy

Figure 15 analyses the behavior of the remaining variables under the new scenario.

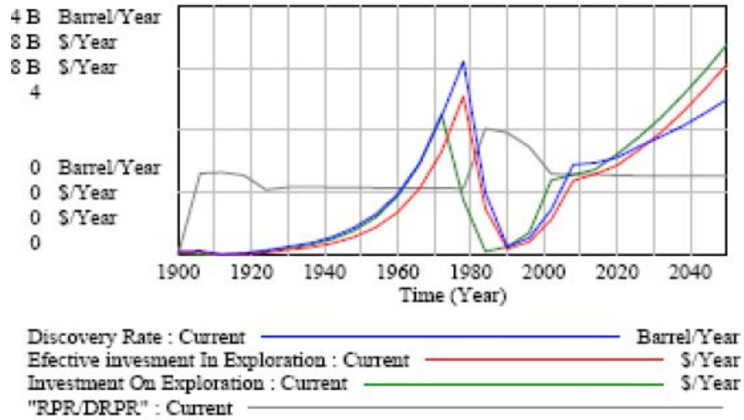

Figure 15. Variable behavior with implementation of new policy

The policy where the government covers 25% of the exploration costs from 1982 onwards has been examined. In this case, the equation for the Cost of Exploration becomes IF THEN ELSE (Time<1982, Graph in Figure 16 FURR), 0.75*Graph in Figure 16 (FURR)), and the results are shown in Figure 16 and Figure 17.

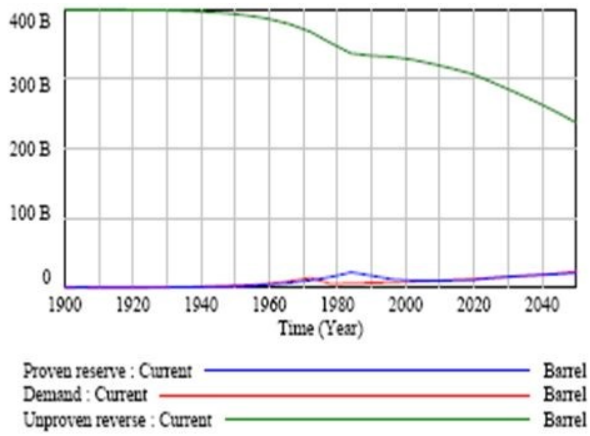

Figure 16. Variable behavior with government participation in exploration

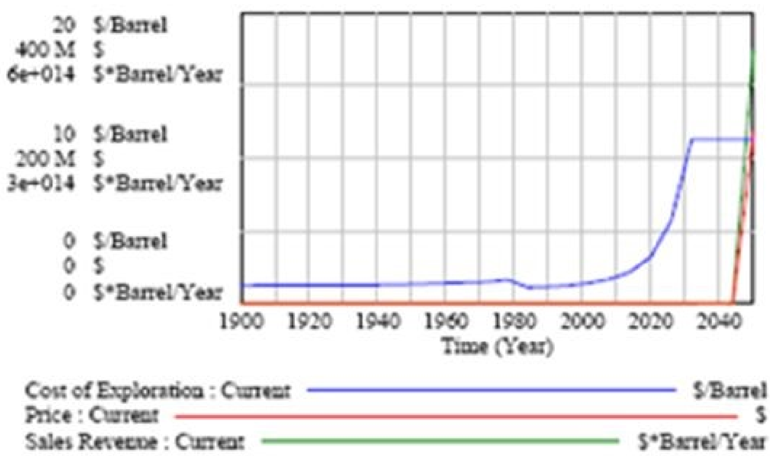

Figure 17. Variable behavior with government participation in exploration

Under these conditions, with the government's intervention, the extraction cost, which had imposed self-sustaining conditions, decreases, and the extraction rate increases. Consequently, the discovered reserves will increase, and the reserve-to-consumption ratio will increase, naturally leading to a decrease in price and a downward trend in investment.

5. Conclusion and recommendation for future reserech

There is no doubt that oil, this God-given resource, is depleting. From the results of this research, the need to review the macro policies in the areas of exploration, extraction, and consumption emerges. Greater focus on shared oil-rich regions, presentation of an optimal consumption pattern, changing the fuel preferences of factories and industries to non-fossil fuels, and greater private sector participation in exploration and production alongside proper consumption management can temporarily save countries from the potential crisis facing this industry and lead them to calmer shores.

In this paper, numerous criteria and indicators were proposed to evaluate the best possible scenario. Statistics show that OECD member countries, especially the United States, have become more dependent on crude oil compared to past decades, and their vulnerability to oil shocks in the oil production and supply market has increased. Therefore, adopting policies that ensure stability in the operational program of exploration, extraction, and supply of this valuable product, along with optimal consumption management and the provision of alternative fuels, is a measure that delaying it will incur significant costs.

Due to the sensitivity and strategic nature of planning in the oil exploration and extraction industry, it was difficult to access and provide reliable statistics.

- The expectations and demands of the stakeholders were different and wide.
- Due to the presence of some qualitative variables and the lack of reliable sources, it was challenging to adjust the formulation and dynamic equations

As future research:

- It is suggested that through other forecasting techniques, such as the time series model, econometric model, judgmental forecasting model, and Delphi method, the results should be examined and compared.
- According to the conditions and time requirements, new scenarios should be added and analyzed.

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