A Novel Approach to Steam Flooding Economic Analysis

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Abstract

The development of heavy oil reservoirs, particularly in regions such as the Niger Delta, offers substantial potential for increasing hydrocarbon recovery but also poses notable technical and economic challenges for the petroleum industry. Steam flooding has emerged as a prominent technique due to its ability to significantly reduce heavy oil viscosity, thereby enhancing its mobility and facilitating flow toward production wells. However, the economic viability of such operations remains a decisive factor in evaluating their feasibility and large-scale application.

In this study, we present a novel approach to the economic analysis of a locally designed steam flood system, aimed at enhancing heavy oil recovery in the Niger Delta region. Our analysis centers on the use of a natural gas-fired steam boiler over a five-year operational period. The total expenditure is calculated by combining the estimated cost of the heat energy generated and the expense of the local boiler installation. Additionally, we calculate both gross and net revenue over the same duration. Key financial metrics—such as cost of energy (COE), gross revenue, net present value (NPV), and the present value per dollar ($)—are assessed to determine the financial viability of the steam flood system.

Furthermore, we developed an artificial neural network model, utilizing the Bayesian regularization algorithm, to predict the cost of energy required for a steam flood project. The findings illustrate the economic potential of locally designed steam flood systems in optimizing heavy oil recovery in the Niger Delta. This approach not only offers significant economic advantages but also contributes to energy sustainability in the region. The study also underscores the importance of employing simple proxy models in the economic evaluation of steam and hot water flooding projects.

Overall, this analysis provides valuable insights for oil and gas industry stakeholders, demonstrating the economic feasibility and potential returns of implementing local steam flood technology in heavy oil recovery.

Introduction

The exploitation of heavy oil reserves, particularly in regions like the Niger Delta, presents significant opportunities as well as technical and economic challenges for the petroleum industry. Enhanced oil recovery (EOR) techniques are crucial for maximizing the extraction of these reserves. Among the various EOR methods, steam flooding has gained prominence due to its effectiveness in reducing the viscosity of heavy oil, thereby improving its mobility towards production wells (Green and Willhite 1998). Nonetheless, the economic feasibility of such projects remains a critical factor in determining their implementation.

In the Niger Delta, the deployment of locally designed steam flood systems presents a promising strategy for optimizing heavy oil recovery. A comprehensive economic analysis is essential to evaluate the associated costs and potential benefits of these systems. This study introduces a novel approach to assessing the economic performance of a natural gas-fired steam boiler system used for steam flooding over a five-year operational period.

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The analysis encompasses a detailed estimation of total expenditures, including the dollarized heat energy output and the cost of the locally designed boiler.

Key financial metrics, such as net present value (NPV), present value per dollar ($), and discounted cash flow rate of return (DCF-ROR), are employed to assess the economic viability of the steam flooding system. Additionally, an artificial neural network model, utilizing the Bayesian regularization algorithm, is developed to predict the cost of energy required for steam flood projects. This approach emphasizes the utility of straightforward proxy models in the economic evaluation of steam and hot water flooding operations.The results of this study demonstrate the economic potential of locally designed steam flood systems in the Niger Delta, indicating substantial economic benefits and contributions to energy sustainability. These insights provide critical information for stakeholders in the oil and gas industry, offering a deeper understanding of the financial prospects associated with the implementation of local steam flood technologies.

Steam flooding, a thermal enhanced oil recovery (EOR) technique, has been extensively studied for its potential to improve heavy oil production. Its application involves injecting steam into oil reservoirs to reduce the viscosity of the oil, thereby enhancing its mobility and facilitating its extraction. This method has proven particularly effective in regions with significant heavy oil reserves, such as the Niger Delta. The economic viability of steam flooding projects is a critical consideration, necessitating comprehensive economic analyses that encompass cost estimation, revenue projection, and financial performance metrics.

Early foundational work by Prats (1982) detailed the principles and mechanisms of steam flooding, focusing on heat transfer and oil displacement dynamics. These principles have been pivotal in understanding the technical feasibility of steam flooding and setting the stage for subsequent economic evaluations. The economic aspects of steam flooding gained prominence with the work of Alvarado and Manrique (2010), who reviewed various EOR methods and highlighted the importance of cost-effective steam generation and injection processes. They underscored that natural gas-fired steam boilers could be particularly advantageous in regions with abundant natural gas resources.

Babadagli (2012) contributed significantly to the optimization of steam injection parameters to maximize both oil recovery and economic returns. Utilizing advanced reservoir simulation techniques, Babadagli's research evaluated various steam injection scenarios, providing a nuanced understanding of the interplay between technical and economic factors. This study emphasized the need for tailored strategies to enhance the economic outcomes of steam flooding operations.

Fattah et al. (2019) extended the economic analysis to a field-scale steam flooding project in Oman. Their study demonstrated that steam flooding could be economically attractive under specific conditions, particularly when oil prices are favorable, and steam generation processes are efficient. The use of field-scale data provided practical insights into the real-world applicability of steam flooding techniques.

Focusing on the Niger Delta, Hamza et al. (2021) evaluated the economic feasibility of using locally sourced materials for steam generation. Their analysis revealed that natural gas-fired boilers could significantly reduce operational costs, thereby enhancing the project's overall economic viability. This study highlighted the potential for region-specific adaptations to improve the economic outcomes of steam flooding operations.

The economic evaluation of steam flooding projects commonly employs metrics such as net present value (NPV), internal rate of return (IRR), and discounted cash flow rate of return (DCF-ROR). NPV measures the profitability of a project by discounting future cash flows to their present value, providing a clear indicator of the project's financial viability. IRR represents the expected rate of return, while DCF-ROR offers insights into the rate of return considering the time value of money. These metrics are crucial for making informed investment decisions and optimizing financial performance.

Advancements in economic modeling and simulation have enabled more accurate predictions of steam flooding performance and economic outcomes. These tools facilitate the optimization of steam injection parameters, cost management, and risk assessment, thereby enhancing the decision-making process for EOR projects. The integration of economic and technical analyses ensures a holistic approach to evaluating steam flooding projects, addressing both feasibility and profitability.

The economic analysis of steam flooding has evolved significantly, with recent studies providing valuable insights into its feasibility and profitability. The findings from various regions, including the Niger Delta, demonstrate that steam flooding can be a viable option for enhancing heavy oil recovery, provided that efficient steam generation and cost management strategies are employed. Future research should continue to focus on optimizing steam injection parameters and exploring the use of locally sourced materials to further improve the economic outcomes of steam flooding operations.

Methodology

The methodology involved the sourcing of core-flood dataset from literature, utilizing heat and economic equations to extrapolate more datasets, and developing predictive Artificial Neural Network models to predict the cost of energy requirements for various steam projects. The study was carried out using some basic assumptions which are summarized in **Table 1**.

Table 1—Steam flood assumptions.

Parameters	Value
1 Barrel of oil	$50
OOIP (Heavy Oil Reservoir)	5,000,000 bbl
1BTU of energy	$0.0075154
Production Duration	5years
Hot Water/Steam flow rate (field)	2917 kg/hr
Energy content of a 150L (85% Butane, 15% Propane) LPG	4,064,440 BTU
150 Liters of LPG (85% Butane, 15% Propane)	75kg; $75

Economic Analysis

Key equations utilized for developing the economic analysis are as follows.

$$\text{Yearly oil production(bbl)} = \text{Daily oil production}\left(\frac{\text{bbl}}{\text{day}}\right) * 365, \qquad (1)$$

$$\text{Recovery Rate} = \text{q}\left(\frac{\text{ml}}{\text{min}}\right) * \frac{1440}{158{,}987}\left(\frac{\text{min.bbl}}{\text{ml.day}}\right) * \frac{\text{OR (ml)}}{69.96} * 2917, \qquad (2)$$

$$\text{Gross Revenue(\$)} = \text{OP (bbl)} * 50\ \left(\frac{\$}{\text{bbl}}\right), \qquad (3)$$

$$\text{Local Steam Generator cost (\$)} = \frac{\text{M}\left(\frac{\text{kg}}{\text{hr}}\right) * \text{Cs (\$)}}{\text{m}\ \left(\frac{\text{kg}}{\text{hr}}\right)}, \qquad (4)$$

where M represents the field scale steam flow rate, kg/hr; Cs is the lab scale local steam generator cost, $; m is the lab scale steam flow rate, kg/hr; m is from experimental analysis, kg/hr.

Table 2 gives the summary of the core flood literature that was utilized in the economic analysis. The cost of energy was estimated from the knowledge of the cumulative heat energy to be expended over the 5-year duration. **Table 3** gives the CAPEX analysis of the laboratory scale boiler, which was then magnified 2917 times up to the field scale.

Table 2—Laboratory core flood results (Odo 2024).

Coreflood Number	Core Porosity (Fraction)	Core Permeability md	Oil Density g/cc	Hot water or Steam injection Temperature ℃	Actual Cumulative Oil Produced (ml)
1	0.26	3429.44	65.83	50.00	49.14
2	0.29	9807.04	66.01	52.04	54.05
3	0.25	4268.59	65.82	54.08	48.05
4	0.27	5443.42	66.02	56.12	50.17
5	0.27	6618.24	65.72	58.16	50.76
6	0.27	6114.74	65.79	60.20	50.98
7	0.25	3765.10	66.04	62.24	47.62
8	0.27	6450.41	65.89	64.29	50.24
9	0.25	7793.06	65.96	66.33	46.98
10	0.25	4772.09	65.69	68.37	46.89
11	0.29	4939.92	65.90	70.41	54.28
12	0.27	9135.71	65.95	72.45	51.48
13	0.25	7289.56	65.81	74.49	47.89
14	0.28	9471.38	65.84	76.53	53.20
15	0.29	4100.76	65.98	78.57	54.27
16	0.26	9639.21	66.00	80.61	48.66
17	0.27	2925.94	66.03	82.65	52.17
18	0.25	5779.08	65.99	84.69	47.48
19	0.26	1751.12	65.55	86.73	50.92
20	0.24	9303.54	65.93	88.78	46.03
21	0.28	4604.26	65.68	90.82	52.06
22	0.27	2758.11	65.66	92.86	51.36
23	0.24	8128.72	65.63	94.90	46.26
24	0.25	3261.60	65.86	96.94	48.12
25	0.25	3093.77	65.87	98.98	47.45
26	0.28	8632.22	65.73	101.02	52.89
27	0.28	8464.39	65.74	103.06	52.21
28	0.29	3597.27	65.97	105.10	54.05
29	0.26	8967.88	65.94	107.14	49.21
30	0.25	7121.73	65.92	109.18	48.08
31	0.29	2422.45	65.67	111.22	54.75
32	0.27	9974.87	66.05	113.27	50.22
33	0.28	5946.91	65.61	115.31	52.57
34	0.26	8800.05	65.57	117.35	48.34
35	0.27	2086.78	65.60	119.39	52.29
36	0.24	7625.23	65.62	121.43	45.93
37	0.24	2254.61	65.75	123.47	47.47
38	0.28	4436.43	65.78	125.51	52.26
39	0.25	2590.28	65.65	127.55	49.11
40	0.24	6786.07	65.70	129.59	45.80
41	0.28	6953.90	65.91	131.63	53.17
42	0.28	3932.93	65.64	133.67	53.25
43	0.26	5275.58	65.71	135.71	49.84
44	0.28	7960.89	65.56	137.76	52.58
45	0.26	5611.25	65.80	139.80	49.09
46	0.26	5107.75	65.88	141.84	49.33
47	0.26	6282.57	65.58	143.88	49.91
48	0.28	7457.40	65.77	145.92	52.09
49	0.24	1918.95	65.59	147.96	46.77
50	0.27	8296.55	65.76	150.00	51.17

Table 3—Cost analysis of the fabricated boiler (8.5 litres).

	Steam Line	Valves	Thermometer	Pressure Gauge	Vessel	Furnace	Total
CAPEX ($)	15.21	8.34	17.20	11.22	50.13	35.02	137.12

$$\text{Cost Of Energy (\$)} = \frac{Q\ (BTU)}{E} * N\ (\frac{\$}{75kg}), \quad (5)$$

$$\text{Q (Heat Injected) (BTU)} = \left(\text{M}\ \left(\frac{\text{kg}}{hr}\right) * \text{t}\ (hr) * 4.2\ \left(\frac{\text{kg}}{\text{kg.k}}\right) * \text{dt (K)}\right) * 0.948\ (\frac{\text{BTU}}{\text{KJ}}), \quad (6)$$

$$\text{NPV} = \text{GR} - (\text{LSG} + \text{COE}) \quad (7)$$

where M equals 2917 kg/hr.

Thermal Flooding Economic Analysis. Economic analysis was conducted on the production dataset provided in Table 2, and the results are depicted in **Table 4**. The graphical analysis was obtained from the economic results in Table 4. From **Figure 1**, the optimal injection temperature was obtained as 88°C. This implies that flooding at temperatures above 88 °C would lead to wasted energy and incur significant losses for the operating company.

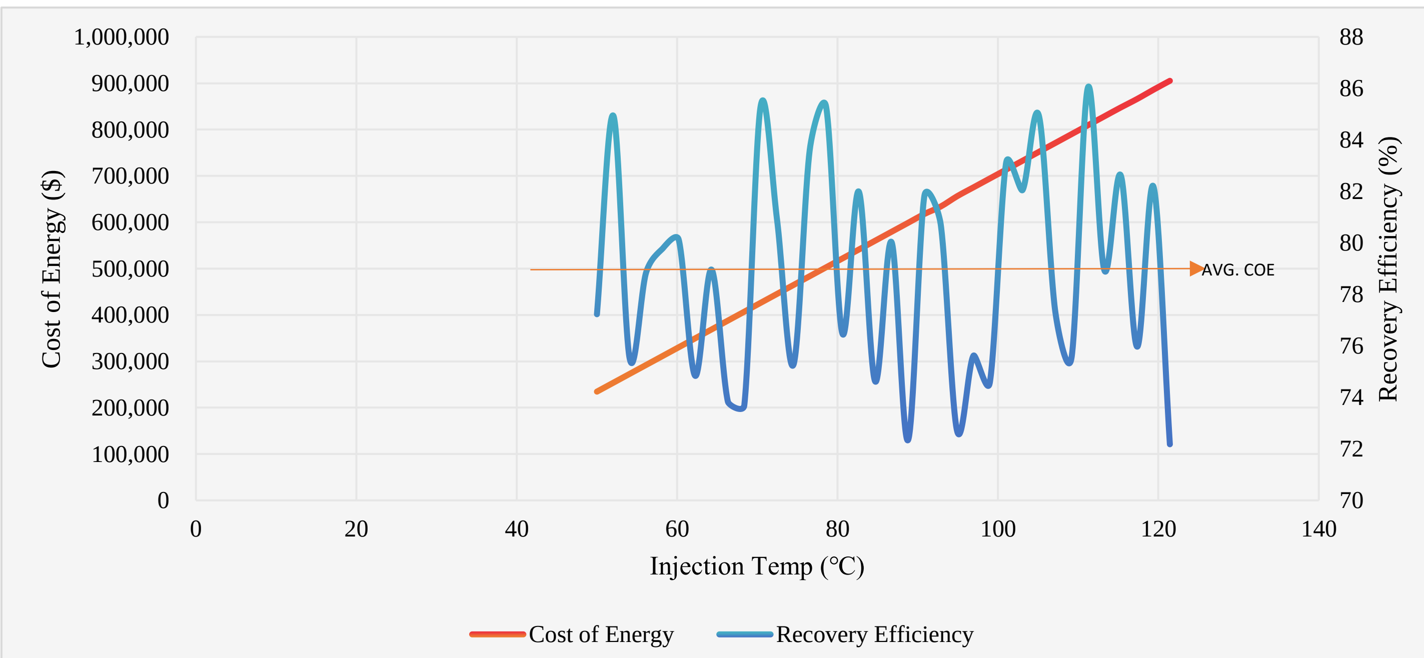

Figure 1—Optimal injection temperature determination.

Figure 2 depicts the increment of net revenue with an increasing production rate. However, this illustration alone doesn't give the full economic view of the project, as there was no observed direct proportionality (from the data analyzed) between the injection temperature (consequently the cost of energy) and oil production rate.

Table 4—Economic analysis results.

Inj. Temp °C	OOIP (MMbbl)	RR (bopd)	GR (MM$)	LSG CAPEX ($)	COE ($)	REV (MM$)
50.00	5.0	1301.14	189.96	399,979	234,676.02	189.33
52.04	5.0	1493.71	218.08	399,979	253,825.59	217.43
54.08	5.0	1383.51	201.99	399,979	272,975.15	201.32
56.12	5.0	1502.62	219.38	399,979	292,124.72	218.69
58.16	5.0	1579.05	230.54	399,979	311,274.28	229.83
60.20	5.0	1644.90	240.16	399,979	330,423.84	239.43
62.24	5.0	1591.61	232.38	399,979	349,573.41	231.63
64.29	5.0	1737.61	253.69	399,979	368,816.84	252.92
66.33	5.0	1679.24	245.17	399,979	387,966.40	244.38
68.37	5.0	1730.30	252.62	399,979	407,115.97	251.81
70.41	5.0	2065.82	301.61	399,979	426,265.53	300.78
72.45	5.0	2018.85	294.75	399,979	445,415.09	293.90
74.49	5.0	1933.49	282.29	399,979	464,564.66	281.43
76.53	5.0	2209.45	322.58	399,979	483,714.22	321.70
78.57	5.0	2316.71	338.24	399,979	502,863.79	337.34
80.61	5.0	2122.32	309.86	399,979	522,013.35	308.94
82.65	5.0	2295.54	335.15	399,979	541,162.91	334.21
84.69	5.0	2107.49	307.69	399,979	560,312.48	306.73
86.73	5.0	2279.83	332.86	399,979	579,462.04	331.88
88.78	5.0	2078.74	303.50	399,979	598,705.47	302.50
90.82	5.0	2371.14	346.19	399,979	617,855.04	345.17
92.86	5.0	2359.08	344.43	399,979	637,004.60	343.39
94.90	5.0	2142.67	312.83	399,979	656,154.16	311.77
96.94	5.0	2247.39	328.12	399,979	675,303.73	327.04
98.98	5.0	2234.40	326.22	399,979	694,453.29	325.13
101.02	5.0	2510.98	366.60	399,979	713,602.86	365.49
103.06	5.0	2498.84	364.83	399,979	732,752.42	363.70
105.10	5.0	2607.76	380.73	399,979	751,901.98	379.58
107.14	5.0	2393.23	349.41	399,979	771,051.55	348.24
109.18	5.0	2356.82	344.10	399,979	790,201.11	342.89
111.22	5.0	2704.90	394.92	399,979	809,350.67	341.71
113.27	5.0	2500.57	365.08	399,979	828,594.11	363.85
115.31	5.0	2637.86	385.13	399,979	847,743.67	383.88
117.35	5.0	2444.26	356.86	399,979	866,893.23	355.59
119.39	5.0	2664.16	388.97	399,979	886,042.80	387.68
121.43	5.0	2357.84	344.24	399,979	905,192.36	342.93

Note: CAPEX of local steam generator was estimated using the relationship, LSG $= \frac{2917*132}{1} = \$399{,}979$

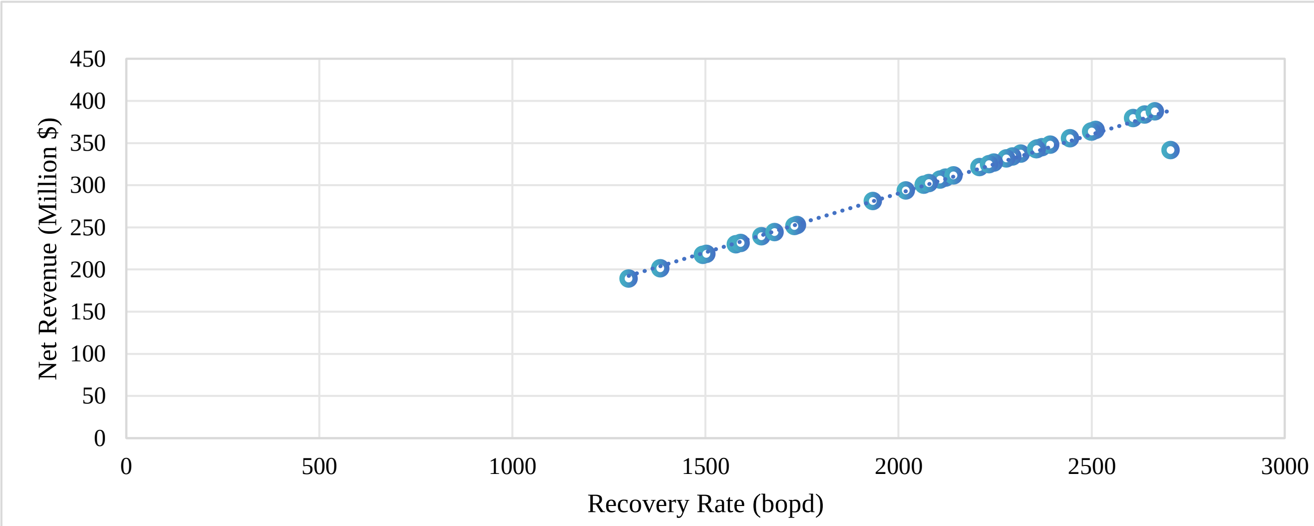

Figure 2—Net revenue analysis.

ANN model Development for Cost of Energy Estimation. Artificial neural network models were developed to predict the cost of energy requirement, with the knowledge of the injection temperature, recovery rate, and the gross revenue as input parameters. Bayesian regularization was utilized to train a random 70% of the data from Table 3 over 1000 epochs, and the training results, R-value and mean squared error were all gotten and utilized. The ANN model consisted of four input layers, three hidden layers, and two output layers. **Table 5** gives the input parameters utilized in developing the Artificial Neural Network model coupled with their descriptions. The values were normalized to improve model accuracy and obtain data consistency.

Table 5—Model development input parameters.

Input Parameter	Description	Unit
Temp	Hot water injection temperature	ºC
RR	Crude oil recovery rate	bbl/day
GR	Gross revenue from the cumulative production	$
RE	Recovery Efficiency	%

Figure 3 gives the network architecture of the developed ANN model. Three input parameters were utilized in building the model, and the weights and biases were a function of two hidden layer neurons, in which two outputs (cost of energy and payout) were obtained.

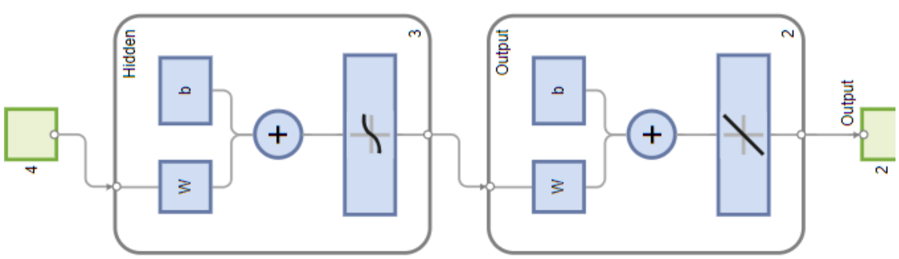

Figure 3—Developed ANN model.

Figure 4 gave the plot and R-score of the training, validation and test datasets. A good accuracy was observed in the validation, with an R-squared value of 0.98974 over the 1000 epochs. The training and test analysis, as expected, had better R-squared values with 0.99959 and 0.99965 respectively.

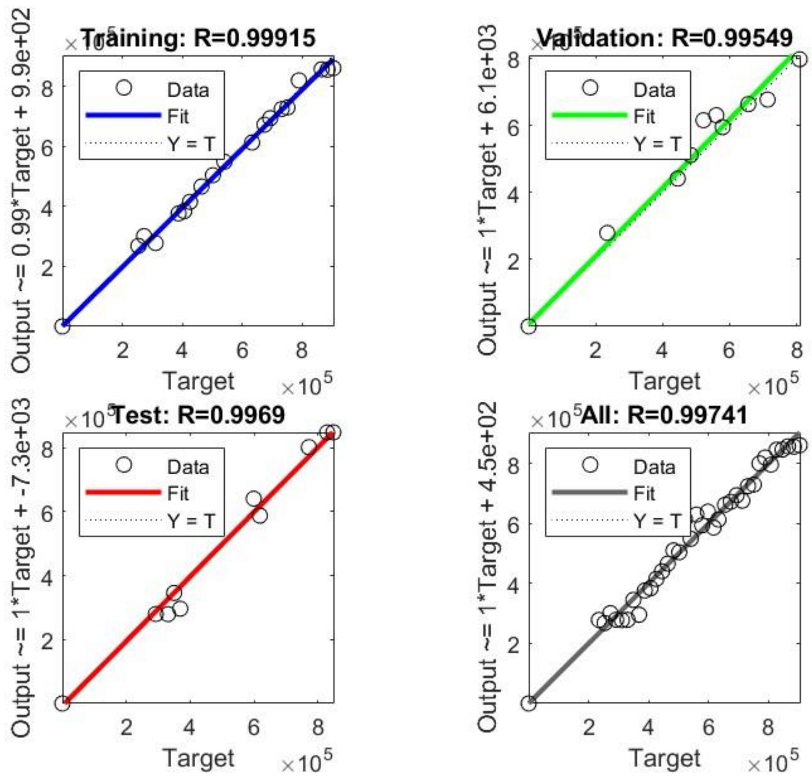

Figure 4—Training, test and validation results.

Table 6 gives a summary of the model type utilized and the results obtained from the entire machine learning operation. The MSE and R-Square results for the training, test and validation datasets are attached.

Table 6—Model development results

Data Division		Random
Model		Levenberg Marquardt
Input layer size		3
Hidden layer size		3
Output layer size		1
Training	MSE	0.0050
	R^2	0.9992
Validation	MSE	0.0023
	R^2	0.9955
Test	MSE	0.0004
	R^2	0.9969

Figure 5 shows the training performance over 1000 epochs. Further investigation gave the best training performance on the 1000^{th} epoch, with a mean squared error of 0.025306.

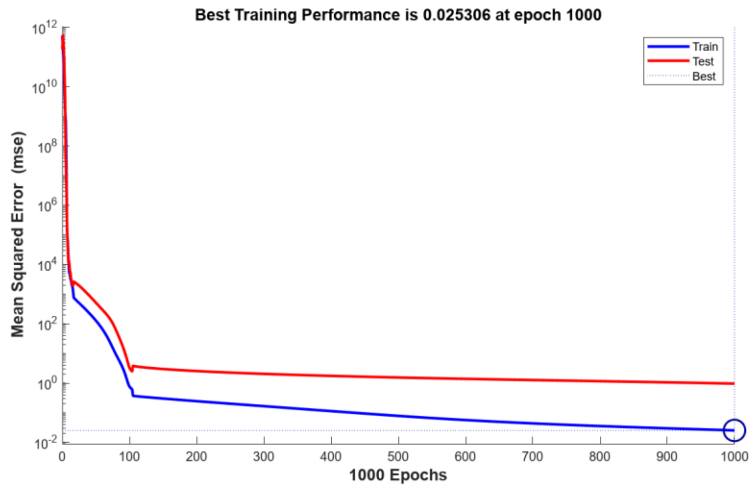

Figure 5—ANN model training performance results.

In **Figure 6**, the training state of the entire Bayesian analysis is summarized, spanning from the gradient to the sum squared parameters over the entire 1000 epoch.

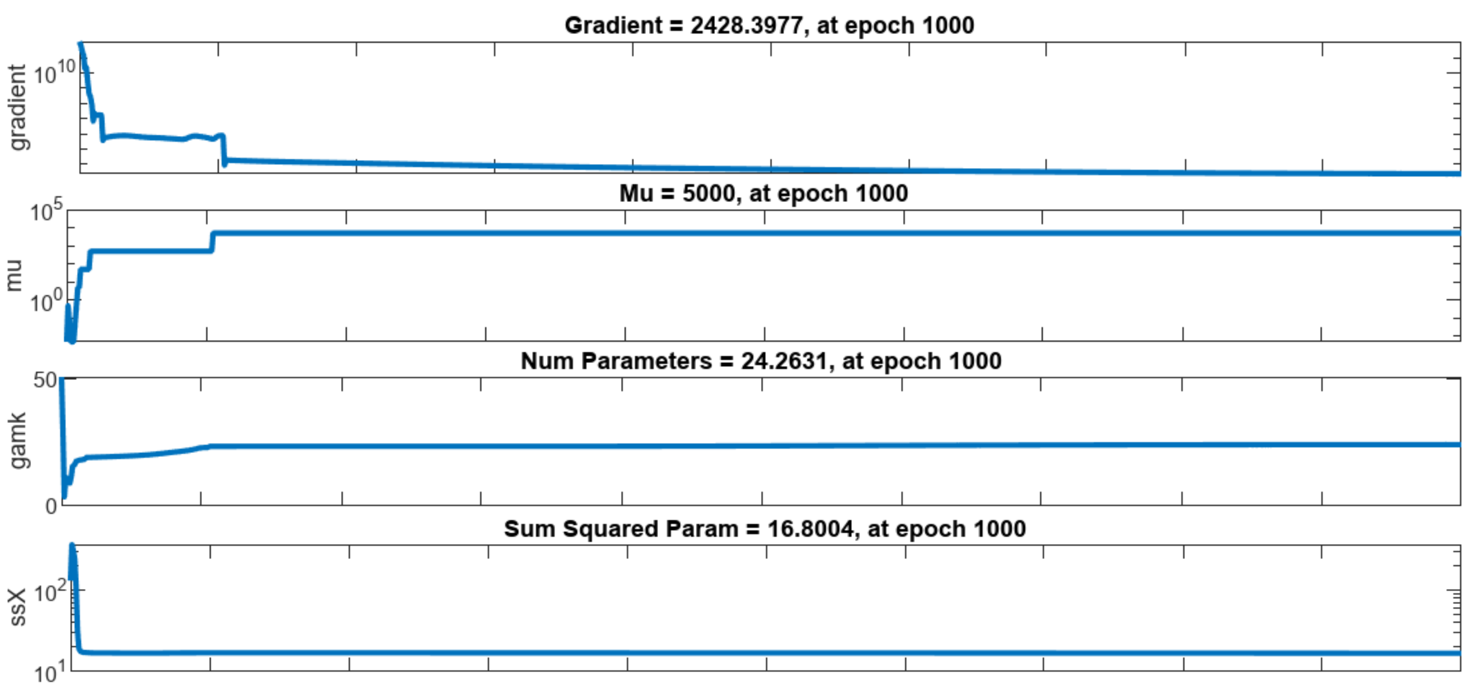

Figure 6—Training State plot of the analysis.

Table 7 gives a detailed analysis of three key economic indicators of the steam flood project, which include the NPV, P/$, and payout duration. Graphical plots were done to further explain the economic relationships and harmonize with Figures 1 and 2 to obtain the best injection strategies for optimal oil production.

Table 7—Economic analysis results.

Inj. Temp (°C)	Net Present Value (MM$)	Profit per Dollar (P/$)	Payout Duration (Years)
50.00	189.33	298.32	0.0034
52.04	217.43	332.56	0.0030
54.08	201.32	299.16	0.0033
56.12	218.69	315.98	0.0032
58.16	229.83	323.13	0.0031
60.20	239.43	327.81	0.0031
62.24	231.63	309.02	0.0032
64.29	252.92	328.98	0.0030
66.33	244.38	310.15	0.0032
68.37	251.81	312.00	0.0032
70.41	300.78	364.03	0.0027
72.45	293.90	347.65	0.0029
74.49	281.43	325.52	0.0031
76.53	321.70	364.04	0.0027
78.57	337.34	373.64	0.0027
80.61	308.94	335.08	0.0030
82.65	334.21	355.11	0.0028
84.69	306.73	319.41	0.0031
86.73	331.88	338.85	0.0030
88.78	302.50	302.90	0.0033
90.82	345.17	339.12	0.0029
92.86	343.39	331.14	0.0030
94.90	311.77	295.20	0.0034
96.94	327.04	304.14	0.0033
98.98	325.13	297.08	0.0034
101.02	365.49	328.21	0.0030
103.06	363.70	321.08	0.0031
105.10	379.58	329.53	0.0030
107.14	348.24	297.38	0.0034
109.18	342.89	288.10	0.0035
111.22	341.71	282.56	0.0035
113.27	363.85	296.16	0.0034
115.31	383.88	307.66	0.0033
117.35	355.59	280.68	0.0036
119.39	387.68	301.46	0.0033
121.43	342.93	262.75	0.0038

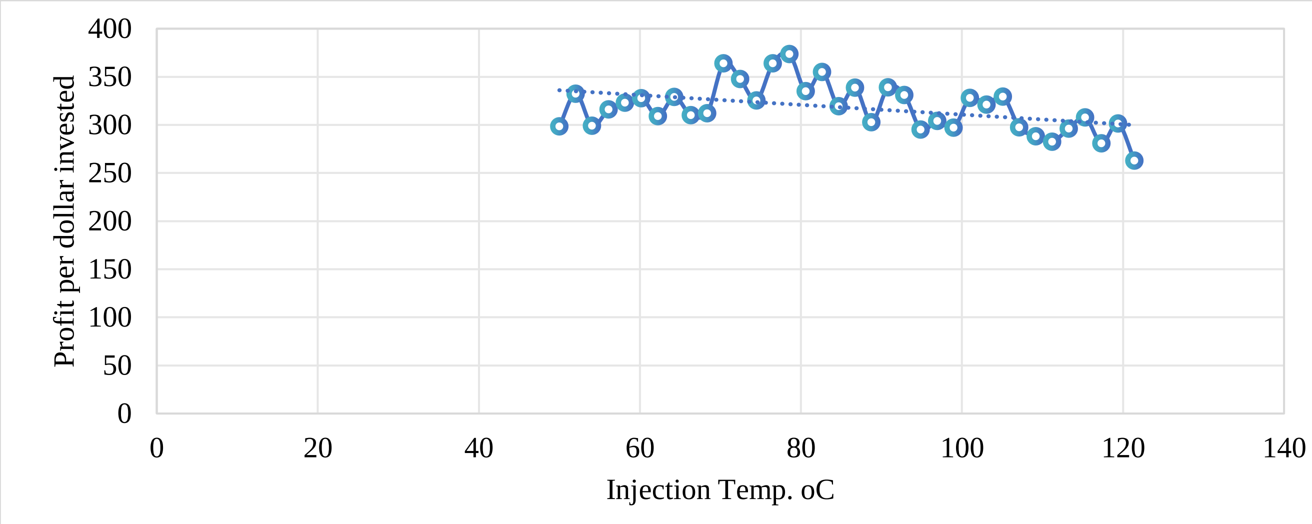

Figure 7—Profit per dollar invested against injection temperature.

Figure 7 shows the relative trend decline of the profit per dollar obtained with an increment in injection temperature. Best results were obtained around the 78-90 ℃(consistent with the previous obtained optimal temperature of 88℃).

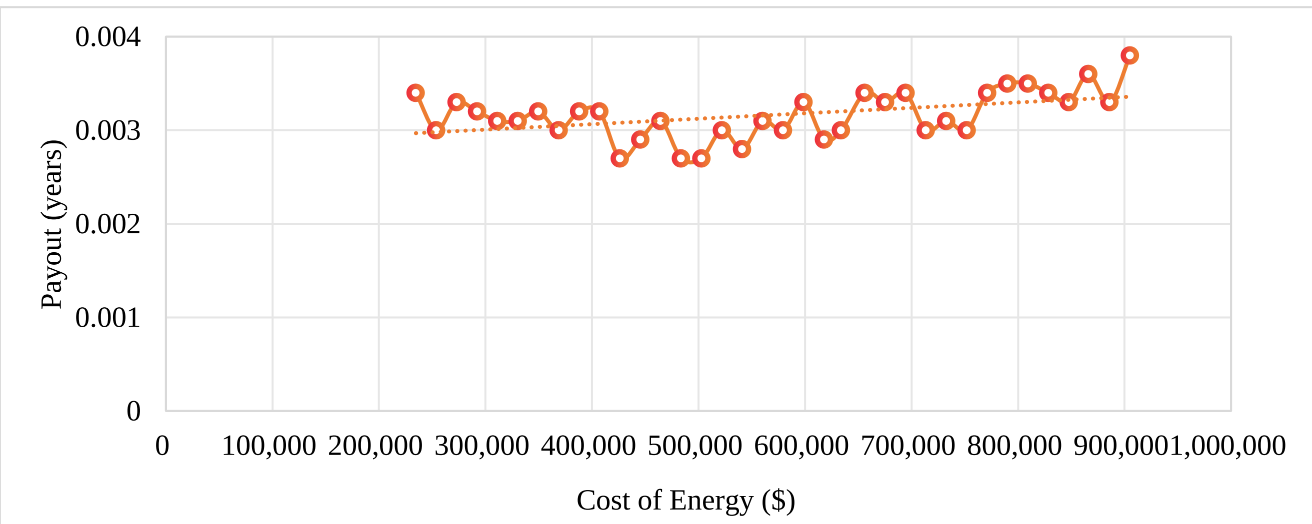

Figure 8—Payout trend with cost of energy.

From **Figure 8**, we observe a gentle sloping upward trend, with the duration of payout averagely increasing as the cost of energy increased. The most favorable payout values (around $500M COE region) coincided with the optimal flood temperature range and fell within the optimal profit per dollar range. This confirmatory trend gives the operating company, from an economic point of view, the range of hot water heating to achieve optimal oil production results. A complimentary analysis with Figure 1, 7 and 8 gives a clearer picture on the optimal injection strategies to obtain optimal economic results.

Conclusion

The conclusions from the above study are summarized as follows:

1. Heavy oil production above the economic optimal temperature leads to exponential monetary wastages.

2. Good correlations were observed between the input parameters and the cost of energy obtained. This is evident from the R-Squared values and mean squared error values.
3. Proxy software developed from the economic equations could have notable on-field uses.
4. The correlations obtained from this study serve as a blueprint for future hot chemical EOR research and field implementation optimization.

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Nomenclature

ANN	=	Artificial Neural Network
BTU	=	British Thermal Unit
CAPEX	=	Capital Expenditures
COE	=	Cost of Energy
DCF-ROR	=	Discounted Cash flow Rate of Return
EOR	=	Enhanced Oil Recovery
GR	=	Gross Revenue
LPG	=	Liquefied Petroleum Gas
LSG	=	Local Steam Generator
NPV	=	Net Present Value
OOIP	=	Original Oil in Place
RR	=	Recovery Rate

Conflicting Interests

The author(s) declare that they have no conflicting interests.

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