Research Article

Integrated Technical and Economical Methodology for Assessment of Undeveloped Shale Gas Prospects: Applying in the Lurestan Shale Gas, Iran

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Shale gas resources can supply the substantial growing demand for clean energy. In comparison with conventional reservoirs, shale gas reservoirs have lower production potential, and selecting the most favorable areas from the broad region of shale gas prospect is very crucial in commercial development. These areas are screened regarding some key evaluation indicators that affect the ultimate recovery of shale gas reservoirs. Many attempts have been made to screen sweet spots by applying the different evaluation indicators. These studies mainly focus on geological sweet spot identification without considering the economic indicators that may influence the order of geological sweet spots for development. The current study introduces a methodology for selecting the best techno-economic spots in undeveloped shale gas regions by integrating the technical and economic criteria. The techno-economic areas are defined as the geological sweet spots with the highest rate of return under the currently employed technology. The economic objective functions for selecting these areas are net present value, internal rate of return, and payback time. To estimate the unknown features for integrating the technical and economic criteria in undeveloped areas, an analog study is applied. Due to the large number of unknowns and uncertainties in shale gas evaluation and low confidence of deterministic results, a probabilistic approach is used. As the first attempt in shale gas assessment in Iran, the Lurestan shale gas region is evaluated by applying this approach. The results indicate that no selected geological sweet spots in this region are commercial regarding the current cost rates and the available technology in Iran, and it can be considered as a future affordable source of energy.

1. Introduction

Conventional reservoirs dwindle in parallel with rising energy demands. Many techniques and approaches (reservoir-based and well-based) have been applied to enhance the ultimate recovery of available conventional reservoirs [1–7]. One of the main substitutes for conventional reservoirs are unconventional resources, especially shale gas resources [8]. In recent years, with the development of horizontal drilling and hydraulic fracturing, shale gas reservoirs have an essential share in the energy portfolio [9, 10].

Shale gas reservoirs are more complicated with respect to conventional reservoirs because they have more complex nature and the broader prospect region. Hence, quantification and production of these resources encounter a higher risk [11]. To reduce the risk in shale gas production, favorable areas with better geological and reservoir properties are selected for exploration of drillings and development. These areas are known as sweet spots [11–16].

Total organic carbon (TOC), effective shale thickness, depositional depth, gas content, thermal maturity (Ro), mineral contents, and mechanical properties are the most common criteria usually applied to screen the broad shale gas region for selecting the sweet spots [11–16]. Many attempts have been conducted by various means to identify sweet spots in shale gas regions [16–24].

Successful exploration and development of shale gas reservoirs have started in North America. Other countries...
lag far behind the U.S. in developing shale gas with early exploration stages or production on small scales and regard it as a future energy source [10]. Shale gas regions with different exploration degrees need different assessment approaches for greater exploration and appraisal activity. The analogy study is suggested for areas with limited data and low exploration degree [25]. Usually, undeveloped shale gas regions are compared with developed shale plates in U.S. and Canada. The analogy study can be categorized as qualitative, semiquantitative, and quantitative [26–30].

All these researches tie some set of favorable properties to locating shale gas sweet spots without conducting the economic assessment. The geological sweet spots are not necessarily commercial, and geologic evaluation should be tied for economic evaluation. These disciplines traditionally have not been integrated in techno-economic shale gas evaluation, especially in undeveloped regions with many unknowns.

The current study introduces an approach for locating the best techno-economic shale gas regions in undeveloped regions. The geological sweet spots were screened regarding the key geological indicators in shale gas evaluation. The analogy study was used to estimate unknown necessary parameters for integrating the geologic and economic criteria to locate the best techno-economic area and estimating the value of economically recoverable reserve (ERR). The geological sweet spots were economically assessed by evaluating net present value (NPV), IRR, and payback time through a probabilistic approach (P10, P50, and P90). As a case study, the Lurestan shale gas region was assessed by applying the aforementioned approach. The economic analysis was conducted regarding the unit cost rates in Iran.

2. Methodology

The approach presented here is designed to locate the best techno-economic shale gas areas in undeveloped regions. Figure 1 represents the workflow of the presented approach. This approach includes six phases as follows:

(i) Identification of geological sweet spots
(ii) Analogy study
(iii) Estimation of drainage area and required well number
(iv) Estimation of the technically recoverable reserve (TRR), and estimated ultimate recover per well (EUR/well)
(v) Production profile estimation
(vi) Economic analysis

2.1. Identification of Geologic Sweet Spots. The geological sweet spots are regions thicker than 30 m with TOC content above 2 wt.%, gas content above 2.5 m³/tone, and Ro greater than 1.2 wt.%. These cutoff values are used regularly in shale gas evaluation [11, 20].

2.2. Analogy Study. Since there is no production data in undeveloped shale gas regions, the analogous shale plate with high exploration level and abundant data can provide the necessary data (average production profile of a well, recovery factor (RF), and average horizontal leg section length) for techno-economic evaluation of undeveloped shale gas regions. The criteria usually utilized for analogy study are brittle mineral percentage, clay content, free to adsorbed gas ratio, pressure gradient, effective reservoir thickness, and fracture intensity.

2.3. Estimation Drainage Area and Required Well Number. For economic evaluation of selected geological sweet spots, estimating the drainage area of each well and consequently calculating the required number of wells in each spot is necessary. In shale gas reservoirs, the drainage area is typically constrained around the fracture network area due to extremely low matrix permeability.

Dong et al., by analyzing many shale gas wells and plays in the United States, established a typical width for the drainage area of the shale gas reservoir to be 1000 ft, and for both ends, the margin from the end of the horizontal well to the boundary of the drainage area was established to be 400 ft (Figure 2). [31]. Regarding the Dong assumption, the drainage area (Dw) of the well with the horizontal leg section length of HL can be calculated by equation (1). Thus, the well spacing depends on the lateral length of the shale well:

\[
D_w = 1000 \ast (\text{HL (ft.)} + 800). \tag{1}
\]

The drainage area determines the required number of wells (Wn) in each geological sweet spot. Equation (2) shows how Wn is calculated. In this equation, Ags is the area of each geological sweet spot.

\[
W_n = \frac{A_{gs}}{D_w}. \tag{2}
\]

2.4. Estimation of the TRR and EUR/Well. TRR is the amount of technically recoverable gas and is estimated by multiplying the original gas in place (OGIP) by RF (equation (3)). The RF is extracted from an analogous shale plate because there is not any choice to estimated RF in undeveloped shale gas region:

\[
TRR = \text{OGIP} \ast \text{RF}. \tag{3}
\]

Regarding the values of Wn and TRR, the value of EUR/Well is calculated by the following equation:

\[
\text{EUR/Well} = \frac{\text{TRR}}{W_n}. \tag{4}
\]

2.5. Production Profile Estimation. The production profile in each geological sweet spot can be estimated from its analogous shale plate. Regarding the general shape of the analogous shale plate and the estimated EUR/Well in each spot, the production profile is adjusted so that the area under
the production profile matches the estimated EUR/well through 25 years (Figure 3). The area under the production profile curve is equal to the estimated EUR/well.

2.5.1. Economic Analysis. Economic analysis is the last step in selecting the best techno-economic areas in undeveloped shale gas regions. Objective functions in the economic assessment are NPV, IRR, and payout time. Regarding the Madani and Holditch (2011) approach, each geological sweet spot with IRR greater than 20% and a maximum 5-year payout is economical. ERR is the amount of economically recoverable gas in the techno-economic spot. The economic evaluation is conducted applying a probabilistic approach, which regards the uncertainty of input data, including gas price, capital expenditure (CAPEX), operational expenditure (OPEX), RF, and discount rate (DR). CAPEX in shale gas mainly includes costs related to rig, casing/cementing, 

FIGURE 1: The methodology of techno-economic sweet spot identification.
fracking, and completion fluid/proppant. OPEX is related to water disposal, labors, pumping/compression energy costs, gathering, transport, and processing costs.

3. Case Study

3.1. Geological Setting. In comparison with North America, a few research studies have been conducted on shale gas resources in the Middle East [32]. Recent investigations of shale gas reservoirs in Iran led to the recognition of two main organic-rich shale formations (S1 and S2) within the Lurestan area [32–37]. This prospect is a part of the Zagros fold-thrust belt and is confined with Zagros reverse fault and Dezful embayment [34, 38, 39]. This prospect is widely extended, and since there is no production test, a reliable strategy for assessing the prospect and selecting the best techno-economic regions with the usual development costs is needed.

The average RF in the Eagle Ford shale plate is 31% (probability distribution of RF is Pearson 5), and the average length of the horizontal leg in the Eagle Ford shale wells is about 6655 ft. [40]. Regarding these values and by applying equations (1) to (4), the values of D_w, W_n, TRR, and EUR/well in each geological sweet spot was calculated. Table 2 represents the exact value of W_n and P10–P50–P90 values of TRR and EUR/well for all geological sweet spots.

The last phase in the techno-economic evaluation of shale gas is the economic analysis and, subsequently, estimating the ERR. The required well number per year depends to production strategy. The production strategy in this study is to have a maximum allowable plateau for 25 years in each geological spot. Hence, the required wells (Table 2) in each spot were planned regarding this strategy. Considering this assumption, the plateau rate and the required well number per year in all geological sweet spots were estimated. Figure 6 shows the plateau rate in selected geological sweet spots.

Table 3 summarizes the selected economic input (considering the unit costs in Iran) in the cash flow model. The drilling cost for each well is estimated regarding a single wellbore, which completed in two S1 and S2 formations.

4. Results and Discussion

The defined cutoff for reservoir thickness, thermal maturity, TOC, and gas content were applied in the Lurestan region to screen the desirable geological areas for further assessment. These cutoffs were applied in the existing static model of the Lurestan region to screen out the unfavorable areas. Shale gas production requires a significant amount of water for fracturing, and the availability of water has a direct effect on the economics of shale gas production. In this study, the assumption is that the required water is supplied from adjacent rivers and water wells. Figure 4 shows the locations of 21 selected geological sweet spots with respect to the protected areas, gas trunk lines, rivers, and water wells. Green areas represent desirable areas, and unfavorable cells are shown in gray color.

To extract the necessary data for further economic analysis, the S1 and S2 formations in the prospect region were compared by some devolved shale plates, including Fayetteville, Marcellus, Haynesville, Utica, Muskwa, Eagle Ford, Barnett, Bossier, and Montney. Many comparison criteria can be select for analogy study. The selection of criteria depends on the objective functions. The main objective functions for finding the analogous shale plate are to extract two key features (production profile and RF). Since these features mainly relate to production potential of shale plates, the parameters, which have the direct effect on production potential, are selected. Figure 5 depicts the normalized value of the comparative criteria including, clay content (C), brittle mineral percentage (BI), adsorbed gas ratio (A), effective reservoir thickness (H), pressure gradient (PG), and fracture intensity (FI) in S1 and S2 formations and the aforementioned plates.

Applying equation (5) for commutative criteria shows that the Eagle Ford shale plate has the least difference with S1 and S2 formations, and this shale plate was considered as the analog in further assessment of the Lurestan shale gas region (Table 1).

\[
\text{analogous plate} = \min \left( (C_{\text{Plate}} - C_3)^2 + (BI_{\text{Plate}} - BI_3)^2 + (A_{\text{Plate}} - A_3)^2 + (H_{\text{Plate}} - H_3)^2 + (PG_{\text{Plate}} - PG_3)^2 + (FI_{\text{Plate}} - FI_3)^2 \right)^{0.5}.
\]
Figure 4: Locations of geological sweet spots.

Figure 5: The normalized value of critical characteristics used for analogy study.

Table 1: Comparison of S1 and S2 formations with developed shale plates in the USA and Canada.

| Shale plate | Marcellus | Barnett | Woodford | Fayetteville | Haynesville | Bossier | Muskwa | Eagle Ford | Utica | Montney |
|-------------|-----------|---------|----------|--------------|-------------|---------|--------|------------|-------|---------|
| S1          | 10.42     | 8.74    | 8.46     | 12.6         | 12.96       | 15.58   | 7.01   | 4.01       | 13.64 | 4.27    |
| S2          | 10.3      | 8.56    | 8.51     | 12.68        | 13.59       | 16.25   | 9.36   | 4.4        | 15.73 | 8.63    |
Table 2: $W_n$ and P10–P50–P90 values of TRR and EUR/well in geological sweet spots.

| Spot no. | $W_n$ | TRR (TCF) $P_{90}$ | TRR (TCF) $P_{50}$ | TRR (TCF) $P_{10}$ | EUR (BCF/well) $P_{90}$ | EUR (BCF/well) $P_{50}$ | EUR (BCF/well) $P_{10}$ |
|----------|-------|---------------------|---------------------|---------------------|-------------------------|-------------------------|-------------------------|
| 1        | 458   | 3.01                | 3.74                | 4.82                | 6.58                    | 8.16                    | 10.53                   |
| 2        | 247   | 1.33                | 1.65                | 2.13                | 5.38                    | 6.68                    | 8.62                    |
| 3        | 257   | 1.23                | 1.52                | 1.97                | 4.78                    | 5.93                    | 7.65                    |
| 4        | 130   | 0.85                | 1.05                | 1.36                | 6.53                    | 8.10                    | 10.45                   |
| 5        | 45    | 0.24                | 0.30                | 0.39                | 5.36                    | 6.65                    | 8.58                    |
| 6        | 69    | 0.48                | 0.60                | 0.78                | 7.02                    | 8.71                    | 11.23                   |
| 7        | 241   | 1.06                | 1.31                | 1.69                | 4.39                    | 5.44                    | 7.02                    |
| 8        | 263   | 1.42                | 1.76                | 2.28                | 5.41                    | 6.71                    | 8.65                    |
| 9        | 61    | 0.25                | 0.31                | 0.40                | 4.13                    | 5.12                    | 6.60                    |
| 10       | 175   | 0.94                | 1.17                | 1.51                | 5.39                    | 6.68                    | 8.62                    |
| 11       | 61    | 0.38                | 0.47                | 0.61                | 6.23                    | 7.73                    | 9.97                    |
| 12       | 36    | 0.17                | 0.21                | 0.27                | 4.66                    | 5.77                    | 7.45                    |
| 13       | 32    | 0.26                | 0.32                | 0.41                | 8.05                    | 9.99                    | 12.89                   |
| 14       | 33    | 0.17                | 0.21                | 0.27                | 5.12                    | 6.35                    | 8.20                    |
| 15       | 215   | 0.83                | 1.03                | 1.32                | 3.85                    | 4.77                    | 6.16                    |
| 16       | 520   | 2.09                | 2.59                | 3.34                | 4.02                    | 4.98                    | 6.43                    |
| 17       | 147   | 0.49                | 0.61                | 0.79                | 3.37                    | 4.17                    | 5.39                    |
| 18       | 352   | 1.45                | 1.80                | 2.33                | 4.13                    | 5.12                    | 6.61                    |
| 19       | 81    | 0.41                | 0.51                | 0.65                | 5.04                    | 6.25                    | 8.06                    |
| 20       | 68    | 0.21                | 0.26                | 0.33                | 3.05                    | 3.78                    | 4.88                    |
| 21       | 26    | 0.10                | 0.13                | 0.16                | 3.93                    | 4.87                    | 6.29                    |

Figure 6: Plateau rate in selected geological sweet spots.

Table 3: P10–P50–P90 values of economic parameters and RF.

| Name                             | Function       | Mean     | $P_{10}$ | $P_{50}$ | $P_{90}$ |
|----------------------------------|----------------|----------|----------|----------|----------|
| Completion unit cost (MMS/ stage)| Normal         | 0.22     | 0.25     | 0.22     | 0.22     |
| Drilling unit cost ($/ft)        | Normal         | 601      | 692      | 610      | 527      |
| Horizontal/vertical drilling price| Normal        | 1.11     | 1.22     | 1.11     | 1.1      |
| OPEX ($/Mscf)                   | Normal         | 1.38     | 1.54     | 1.38     | 1.38     |
| Gas price ($/Mscf)              | Triangle       | 4.22     | 3.5      | 3.5      | 5.66     |
| DR (%)                          | Normal         | 15       | 18       | 15       | 12       |
| RF (%)                          | Pearson 5      | 32.16    | 25       | 31       | 40       |

Since unit costs and economic parameters may vary depending on many conditions, the probability distribution of these parameters was used in the economic analysis. The completion costs should be regarded based on the real expected costs in the case study. However, there is not any experience in Iran about the hydraulic fracturing and related completion costs; the best decision is to select these costs regarding the analogous shale plates, which was applied in this study. The $P_{10}$, $P_{50}$, and $P_{90}$ values for the gas price were selected regarding the total gas price delivered to Iranian petrochemical, international energy hub, and the real price of exported gas from Iran to neighboring countries. Drilling and completion costs were determined by multiplying specific well design factors (measured depth and number of the fracturing stage) by their specific rates (drilling ($/ft$) and completion ($$/Stage$$)). Other well-cost components have a minor contribution to the capital costs as they usually amount to less than half a million dollars. They comprise equipment to push the products to gathering lines, roads, pumps, compressors, and flow lines. These costs were estimated based on their contributions in Eagle Ford shale plate development. The total well cost was obtained by the sum of all of these subordinate costs. Regarding the contribution of major components of OPEX in the Eagle Ford shale plate and by adjusting these components, a range of 1.3 to 1.55 with an average of 1.38 $$/Mscf was considered for operating cost in the economic evaluation of geological sweet spots in the current study.

Discounted cash flow models for these sweet spots were developed based on the production profile, gas wellhead price, discount rate, and development expenditures. As shown in Table 3, a range of 12 to 18% with an average of 15% was considered for DR in the current study.

Regarding the Madani and Holditch approach, each shale plate with IRR greater than 20 percent and payout time less than 5 years considered economic and most prone for development [41].

Table 4 represents the $P_{10}$–$P_{50}$–$P_{90}$ values of estimated NPV for developing the geological sweet spots. The results show that regarding the current economic cost rates, the NPV for all spots in all conditions is negative; thus, they are not profitable at this condition.
5. Conclusion

The outcomes of the proposed approach for detecting the best techno-economic regions in undeveloped shale gas regions and its implementation in the Lurestan shale gas assessment lead to the following conclusion:

(i) The geological sweet spots are not necessarily commercial and geologic evaluation should be tied by economic evaluation to locate the best techno-economic areas.

(ii) The necessary unknown features of undeveloped areas can be estimated from analogous developed shale plates through quantitative analogy study.

(iii) The evaluation of shale gas in the Lurestan region (the case study) is the first attempt in shale gas evaluation in Iran.

(iv) The analogy study identified the Eagle Ford shale plate as the analog in the Lurestan region.

(v) Regarding the current cost rates in Iran, at any conditions ($P_{10}$-$P_{50}$-$P_{90}$), none of the selected geological sweet spots in the Lurestan region is not economical. Due to the lack of infrastructure, experience and expertise in comparison to US, shale gas extraction in Iran is much more expensive than in U.S., and it is considered as future affordable energy in Iran.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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