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A Critical Review of Shale Gas Production Analysis and Forecast Methods

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Original Research Article

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Abstract: This paper critically reviews methods applied in forecasting production of unconventional gas plays. The review focuses on methodologies suitable for shale gas plays, methodological ability to account for parameter and data uncertainty, as well as suitability for appraising undeveloped shale gas plays. The production analysis and forecast methods reviewed include empirical/decline curves, type curves and analytical/numerical methods applicable to unconventional gas production analysis and forecast. The review shows that most of the studies focus on developed shale gas plays, neither account for shale gas well reservoir heterogeneity nor account for below ground uncertainties-such as reservoir and source rock properties. This study concludes that significant research is needed to address the identified limitations of existing studies.

Keywords: Shale Gas, Recoverable Resource, Decline Curves, Type Curves, Analytical Method.

INTRODUCTION

Shale gas, tight gas, coal bed methane (CBM) is unconventional gas resources; the term unconventional refers to the characteristics (typically low permeability) of the source rock and not the composition of the gas [1]. Shale gas production in the United States (US) aided by innovations in drilling techniques boosted domestic gas production previously on a decline [2-5].

The drilling technique used in collecting the gas can be vertical, horizontal or both but accompanied by hydraulic fracturing which increases the permeability of the source rock [6]. An increase in energy demand, declining production from conventional reservoirs and increased growth of oil and gas production from unconventional reservoirs due to technological improvements have led to an increased rate of development in unconventional resources over the past decade [7].

Shale gas reserves and reservoirs have been analyzed around the world however development has been stalled due to a variety of issues one of which is an accurate production forecast. As such the future potential for shale gas production remains unclear regarding the resource size and the recoverable resource size being fundamental in the ongoing debate [8].

The amount of resource that can be recovered based on present market technology is known as the estimated ultimate recovery (EUR) in the petroleum industry. The EUR is an essential factor for both investors and policy makers in appraising petroleum resources. Estimating economic hydrocarbon reserves are of utmost importance to engineers, investors and governments [9]. Furthermore, a life cycle environmental impact assessment bases its results on the EURs and thus implies recoverable resource estimation impacts environmental policy of shale gas development [10]. Most economists and long-term oriented politicians are interested in the overall benefits of extracting gas against the cost [11]. However to conduct a proper economic appraisal or impact assessment of unconventional gas resources, the foundation relies on the production forecast method applied and the empirical evidence supporting the approach. Application of an unsuitable model could lead to recoverable resource overestimation or underestimation which results in investment and policy distortion.

This paper summarizes and critically reviews approaches and methods used for estimating and analyzing recoverable resources in shale gas plays focusing on shale gas wells. Overall this review does not seek to identify a superior approach to shale gas production analysis and estimation that works best in all contexts but identifies strengths, fundamentals and tradeoffs. The purpose of this review is to identify and appraise the ability and suitability of existing shale gas production analysis and estimation models in undeveloped shale gas plays, accounting for heterogeneity and below ground uncertainty.

The methodological review includes available, published and applied approaches mostly used in the United States and Canada where commercial development of unconventional resources has been established; as such, they provide the empirical evidence relating to recoverable resource estimation.

Following the introduction, Section 2 reviews the concept of production forecast and analysis in unconventional gas plays and provides an overview of the methods based on fundamental relationships. Section 3 compares, evaluates and discusses relevant limitations while Section 4 reveals application experience and Section 5 discusses the consequences of identified limitations as well as concludes the study.

Gas Production Analysis and Forecast Concept

Well evaluation and decline characteristics are fundamental to decision making in the petroleum industry. Kaiser considers EURs and initial production as the two parameters that contribute in defining the commercial viability of unconventional gas plays [12]. Studies and methodologies analyzing and forecasting production from unconventional gas wells are evolving along with the production technology. This section reviews studies on shale gas production analysis and production forecast methods; empirical/decline curves, type curves and analytical/numerical simulation methods.

Empirical Methods (Decline Curve Analysis)

In 1944, Arps presented a paper using decline curves for production analysis which plots the percentage decrease from initial production rate from hydrocarbon wells versus time. Arps proposed three scenarios of production rate decline based on the value of “b”; the decline parameter [13]. Figure-1 reveals the different decline trends associated with the three scenarios.

However, Lee and Sidle reveals that unconventional gas wells have been observed with *“b”* values greater than 1 which yields an infinite reserve estimate applying Arps decline methodology [14]. In addition Arps equation assumes a constant bottom-hole pressure, boundary dominated flow, unchanged drainage area and a constant skin factor [15, 14] but unconventional gas wells violate most of these assumptions especially the flow regime and unchanged drainage area [7]. As such using Arp’s hyperbolic equation in unconventional wells to forecast reserves and production might result in reserve overestimation. A number of studies based on the decline curve method have concentrated on overcoming issues associated with applying Arps equation in shale gas well production forecasts. This sub section focuses on the stretched production decline, power law equation and logistic growth methodologies.

Stretched Exponential Production Decline (SEPD) Method

The stretched exponential function was introduced in 1854 to describe the discharge of capacitors [9]. Many processes manifest stretched exponential behaviors in physics, however, for the first time [16] attempted applying it to unconventional gas reservoirs. The SEPD method comprises of the following parameters; n represents an exponential parameter (dimensionless); $q0$ is the initial gas flow rate (Mscf/Month) and t is production time parameter, τ is the characteristic time parameter for the SEPD model while q is the well flow rate. Equation 1 is the rate expression as a function of time while Equation 2 relates to the estimated ultimate recovery in terms of the SEPD model parameters.

$$q = \; q0\; exp\; \left(-\left(\frac{t}{\tau}\right)n\right) \text{... ...Equation 1}$$

$$EUR = \frac{q0\tau}{n}\Gamma\left(\frac{1}{n}\right) \text{... ... ... Equation 2}$$

Valko and Lee conclude that the SEPD model has definite advantages over Arps’ decline curves for unconventional gas applications based on perceived good mathematical properties [16]. Statton’s 2012 study notes that SEPD models provide a more conservative forecast compared to the Arps model. The SEPD method is considered an empirical model with multiple references in physics’ literature; providing evidence of the stretched exponential function’s ability to model decays in randomly disordered and chaotic systems.

Power Law Equation (PLE)

Johnson and Bollens introduced extrapolation of well decline curves using a loss ratio approach [17]. Ilk *et al.*, employs the power law loss ratio rate to model shale reservoir production based on exponential decline [18]. In addition the study also applies a hyperbolic rate decline relationship (equation 3) with the Power loss ratio decline model guided by equation 4 below.

$$q = q_i \left(\frac{1}{((1+bD_i t)^{\frac{1}{b}}} \right) \text{… … … …Equation 3}$$

$$q = \hat{q}_i \, exp(- D_\infty t - \widehat{D_I} t^n) \text{.............Equation 4}$$

Where $q\ (t)$ is the production rate, $q1$ is the rate intercept, $D1$ represents decline constant after a time unit, D^{θ} is the decline constant at infinite time and n is the time exponent.

The power loss equation models the loss-ratio uniquely by assuming that the loss-ratio follows a power law function at early time and later becomes constant [19]. IIk *et al.*, concludes the power law loss ratio is more flexible as it can be applied to transient, transition and boundary-dominated flow data and by the use of the decline constant at "infinite time" yields an exponential decay at very large times unlike the Arps exponential decline where the decay is constant [18]. Clark states that the power law model has several distinct advantages over Arps exponential model in that a single continuous function is used in forecasting production however concern exist regarding an appropriate value for $D\infty$ the final decline rate and its being arbitrary [7]. In addition, Kanfar states that the PLE is the only method that models both transient and boundary dominated flow [19]. Weijemars however suggests applying a Levenberg-Marquardt minimization technique to account for fluctuation level in the production rate by minimizing the squared difference between the measured and calculated rates resulting in equation 5 for a simple exponential decline [20].

$$q\ (t)\ = q_i exp(-D^{\theta} t)\ + q_i f_n (0.5 - r) \text{…Equation 5}$$

Where $q\ (t)$ is the production rate, qi is the initial production, D^{θ} is the decline factor, fn is the scatter level which varies between 0 and 1 and r which also varies within same range.

Logistic Growth Method (LGM)

Clark proposes the application of the LGM model for analyzing and estimating production from unconventional gas reservoirs although the LGM approach was originally developed for population growth [7]. The LGM is based on the concept that growth is possible only to a certain size [19]. The maximum growth size is referred to as the carrying capacity a multiplicative factor applied to an exponential growth equation. Equations 6 and 7 define the production rate and cumulative forms of the LGM approach.

$$q\ (t) = \frac{dQ}{dt} = Knbt^{n-1}/(a + t^n)^2 \text{ ....Equation 6}$$

$$Q\ (t)\ = Ktn/a + tn \text{ ………………Equation 7}$$

Q represents the cumulative production while q is the production rate. The carrying capacity *K* is the total amount of oil and gas that can be recovered from the well from primary depletion not taking into account economic or time related cutoffs while the *"a"* constant is the time to the power n at which half of the oil or gas has been produced and n the hyperbolic decline exponent [7]. Clark's 2011 study in addition compares LGM to Arps model and considers Arps model more optimistic in reserve forecasting while Kanfar concludes that the LGM is the easiest method to apply [19]. However the LGM approach assumes hyperbolic decline characteristics and requires the estimation of at least two parameters or three parameters at most depending on the availability of well information.

Type Curves

The application of type curve methods requires fitting historical production data with dimensionless solutions to flow equation corresponding to different well/fracture geometries, reservoir types and boundary conditions [21]. Dimensionless solutions are achieved by multiplying a variable by a group of constants with opposite dimensions.

Type curve analysis can be used for forecasting production as well as reservoir characterization [22]. Ilk *et al.*, notes the use of reservoir models for the analysis of reservoir or well performance data has been in practice for over 70 years in the petroleum and hydrology literature [23]. Earlier researches [24], Blasingame and Palacio [25], Wattenbarger *et al.*, [26], and Agrawal [27] develop and apply type curves to unconventional gas wells analyzing past production as well as estimating future production. Recent studies [28]; Nobakht *et al.*, [29] and Clarkson *et al.*, [30] extend type curve application in unconventional gas production analysis addressing and incorporating previously ignored effects and variables. This sub section of the review focuses on Fetkovich [24], Blasingame and Palacio methods as well as other recent studies based on type curves [25].

Fetkovich

Clarkson notes Fetkovich produced the first generation type curves which combined analytical solutions for constant flowing pressure radial flow of liquids with Arps' empirical decline curve for boundary dominated flow [21, 24]. The validity of the Fetkovich type curve is regarded valid for production at a constant bottom hole pressure [23, 24]. The Fetkovich type curve revealed the ability of production data analysis to generate reservoir property estimates comparable to results derivable from pressure transient analysis [23]. Fetkovich combined the transient rate and the pseudo-steady state decline curves which resulted in a single phase flow based on material balance and Darcy law [31, 24]. The Fetkovich rate time relationship combines the early time, transient, analytical solutions with Arps's equations for the later time, pseudo-steady-state solutions [27].

Fetkovich *et al.*, regards the method as a forecasting technique achieved by history matching rate-time data with an appropriate type curve [32]. Nonetheless the 1987 study applies the method to a West Virginia gas well as Fetkovich applied to only liquid wells [24]. The study concludes that in low permeable gas reservoirs, reserve estimation and production forecasts could be better developed applying the rate-time data than pressure, gas compressibility and cumulative production relationship approach. However Fetkovich's approach assumes a constant bottom-hole pressure which has limitations in practice [23].

Blasingame

Blasingame and Palacio introduced new methods for production data analysis of single flow in either gas or oil by combining Fetkovoch type curve approach with rigorous liquid and semi-rigorous gas stems [25]. Ilk *et al.*, notes that with the method, continuous changes in the rate and pressure history could be considered while Agrawal *et al.*, considers the method useful for gas in place estimation as well as reservoir permeability and skin [1, 27].

The Blasingame type curve was developed applying a plot of the *(q/Δp)* function's logarithm against the logarithm of appropriate material balance time function [23]. However the developed analytical solution exhibits the harmonic form *(b=1)* for both the variable and constant pressure scenarios as such a material balance pseudotime must be applied in calculating the dimensionless variables [21].

The dimensionless rate and dimensionless decline time is thus defined by the equations below.

$$q_{Dd} = q_D b_{Dpss} \ldots\ldots\ldots\ldots\ldots\text{..Equation 8}$$

$$t_{Dd} = \left(\frac{2\pi}{b_{Dpss}}\right) t_{DA} \ldots\ldots\ldots\text{....Equation 9}$$

Where bDpss is a pseudo steady state parameter derived by Pratikno et al. 2003; *qDd* is the dimensionless decline rate; *qD* is the dimensionless rate; *tDd* is the dimensionless decline time while *tDA* is the dimensionless time based on drainage area. Dimensionless parameter status is achieved by multiplying a group of constants with opposite dimensions.

Recent Type Curve Studies

Bello's 2009 thesis extend's El-Banbi method applying a transient linear flow regime on a linear dual porosity hydraulic fractured shale gas reservoir [33]. The study identifies five regimes and developed equation for four regimes. In addition the study incorporates convergence skin into the linear model to account for its presence in the horizontal wellbore. Clarkson notes that the type curves developed by Bello uses the constant-rate solution and thus unit slope of b=1 during boundary dominated flow applying dimensionless variables for the type curve specifically in gas reservoirs [21, 28].

Furthermore Nobakht reveals that most current formulation for linear flow analysis results in overestimation thereby proposing a new method [34]. The new method analyzes production data under constant flowing pressure, production rate and variable flowing pressure and production rate accounting for desorption and gas slippage. Additionally the impacts of completion heterogeneity is incorporated by extending previous study by Nobakht *et al.*,

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[1] An increase or decrease in the pressure drop predicted with Darcy's law using the value of permeability thickness,kh, determined from a buildup or drawdown test. The difference is assumed to be caused by the "skin." Skin effect can be either positive or negative. The skin effect is termed positive if there is an increase in pressure drop, and negative when there is a decrease, as compared with the predicted Darcy pressure drop. A positive skin effect indicates extra flow resistance near the wellbore, and a negative skin effect indicates flow enhancement near the wellbore. The terms skin effect and skin factor are often used interchangeably. In this glossary, the term skin effect refers to the numerical value of the skin factor.

while a new set of dimensionless type curves are developed for a common conceptual model for multi-fractured horizontal well [29]. The study reveals the impact of completion heterogeneity on long term forecasts.

Analytical methods

Analytical production analysis methods are also known as rate-transient methods which apply a theory similar to pressure-transient analysis with foundation related to the physics of fluid storage and flow [21]. Pressure transient analysis is based on pressure and fluid flow changes over time while rate transient analysis refers to production data applying a similar approach [35]. Lee *et al.*, refers to analytical models as methods applying logically derived mathematical solutions [36]. Transient well analysis includes traditional pressure transient and production analysis [37]. Clarkson states that analytical models are related to simple reservoir characteristics and boundary conditions while simulation models apply more complex mathematical models derived from numerical methods [21]. Wang notes that due to extremely low permeability of shale reservoirs, nonlinear flow mechanism should not be disregarded in flow calculations [38]. The study also proposes the inclusion of reservoir completions in modeling production applying a horizontal well and a numerical model which illustrates gas flow in shale gas reservoirs analyzing flow mechanisms considering non-linear flow mechanisms. However this review focuses on Patzek *et al*.,'s 2013 study [39].

Rock Extractive Index

Patzek *et al*., develop a method based on the physics of fluid flow mechanism in horizontal wells [39]. Felgueroso-Cueto and Juanes [40] note that Patzek *et al*., extends a mathematical model to incorporate more realistic phase behavior applying a universal scaling function and two adjustable parameters for each well [39]: the interface time between hydro fractures and the mass of gas in place that can ultimately be removed. The study suggests transient gas flow lasts for 3months after which gas flows into the fracture planes as if coming from a semi-infinite region. The study proposes gas production into three phases determined by gas pressure diffusion. The initial high gas pressure stage creates a gas production rate proportional to the inverse of the square root of production time. At a further production stage known as the interference time, pressure drops below the initial thus gas production rate reduces relative to the square root of time behavior [39]. Eventually an exponential decay occurs with production proportional to outstanding gas in place. The study establishes a pressure-dependent coefficient describing the diffusion of gas pressure called "hydraulic diffusivity of gas". Gulen *et al.*, [41] notes that Patzek *et al*.,'s 2013 study demonstrates that gas flow is transient and rectilinear for several years in both vertical and horizontal wells which results in the flow equation represented in equation 10 below.

$$q = \frac{2}{\sqrt{\pi\left(\sqrt{K}\emptyset\frac{c}{\mu}\right)}} \frac{Af}{Bg}\left(\frac{\Delta p}{\sqrt{t}}\right). \dots \dots \dots \dots \dots \dots \text{.Equation 10}$$

where *q* is the flowrate, *K* is rock permeability, Ø is rock porosity, *c* is isothermal compressibility, μ is natural gas viscosity, *Af* is area of rock exposed by the hydraulic fracture , *Bg* is formation volume factor, *p* is gas pressure and Δp is pressure between reservoir and fracture pressure while *t* is time.

In addition Gulen *et al.*, [42] comments that Medlock [43]; an independent econometric analysis applying panel data from more than 16,000 wells gives empirical supports to the Rock Extractive Index (REI) approach. The methodology is termed the REI (determined by fitting the equation to observed production); a reduced form of equation 10 is thus obtained to describe the production rate of a well at a certain time *a*.

$$q_{t,i} = (k_i * REI_I)/\sqrt{\tau} \quad \dots\dots\dots\dots\text{Equation 11}$$

Table-1: Arps Decline Scenarios

Exponential	Hyperbolic	Harmonic
(b=0)	(0<b<1)	(b=1)

Table-2: Selected Reviewed Studies Applying Production Analysis and Forecast Methodologies

Study	Analysis/Forecast Method	Parameters Applied	Uncertainty Analysis	Play Type
Kaiser (2012)	Type curves	Initial production distribution and EUR	Gas prices, Expenses and Tax regimes	Developed
Gulen et al. (2013)	Analytic model	Reservior, gas and source rock properties	Sensitivity to gas prices,cost,fiscal regime & probabilistic rate of returns	Developed
Taylor (2013)	Decline curve	Hyperbolic & Decline factor	Scenarios (low, central and high)	Undeveloped prospect
Gray & Koosh (2007)	Type curves	EUR/Well, Historical data	EUR,Costs and Initial Production	Developed
Valko & Lee (2010)	Decline curve	Exponent & time parameter	Probability distribution	Developed
Weijemers (2013)	Decline curve	Average EUR/Well initial production rates	Well productivity ranges, P(10-50-90)	Undeveloped prospect
Kewen & Horne (2003)	Decline curve	Oil recovery, capillary and gravity constant	Not considered	Developed
Agrawal et al. (1999)	Combined type and decline curves	Gas & reservoir properties, performance data	Not considered	Developed
Nobakht (2014), Nobakht & Clarkson (2012)	Type curves	Reservoir & gas properties, hyperbolic decline function	b value sensitivity	Developed
Wang (2014)	Analytical model	Reservoir & gas properties, production rate	Sensitivity study on various analyzed effects	Developed
Bello (2009)	Type curves	Reservoir property & dimensions, gas properties	Not considered	Developed and synthetic prospect
Kovacs-Williams & Clarkson (2011)	Type curve	Reservoir property & dimensions, gas properties	P(10-50-90) on fracture half lengths and gas grid prices into a probability distribution	Undeveloped prospect

Model and Application review

Reviewed Shale Gas Production Forecast Methods Limitations

The literature review shows that researchers and analysts apply different production forecast methods to estimate the EUR. Production estimation methods applied to shale gas production are mostly decline curves, type curves or analytical models.

The SEPD, LGM and PLE methods have made improvements to the shortcomings of the Arps decline approach; an empirical method. The SEPD assumes unconventional wells decline in a randomly disordered and chaotic system while the PLE assumes a decline governed by a power law equation. The LGM is based on the carrying capacity K, a parameter dependent on the EUR. However determining the EUR requires knowledge of the field's recovery factor. Recovery factors of unconventional gas wells have been known to vary. Lee *et al*., and Clark both note that the recovery rates of unconventional gas wells are uncertain [6, 7]. As such the LGM approach is exposed to recovery rate overestimation or underestimation, which in turn impacts the EUR and the carrying capacity K. Applying the LGM, requires unbiased knowledge of the well recovery rate. Overall the limitation associated with empirical models is the need to assume a decline trend hyperbolic or exponential as well as a law guiding the well decay trend. In addition empirical models avoid accounting for reservoir properties or changes in either reservoir conditions or produced fluids.

Type curves as the name suggests are modeled based on reservoir type assumptions. Bello [28] notes that type curves are mostly based on radial reservoir models with dual porosity. Furthermore dual porosity models could be pseudo steady state or transient state types. In addition variations in inner boundary conditions could also be constant pressure and rate, with or without skin and wellbore storage, while outer boundary conditions may well be infinite, semi-infinite or closed reservoir models. Additionally, recently developed type curves have analyzed and incorporated various effects and conditions that impact productivity which was previously ignored by empirical and earlier type curve approaches.

Consequently, the challenge for non-technical analyst and policy makers evaluating the production of unconventional reservoirs applying type curves is what reservoir type and condition should be applied or assumed.

The analytical model developed by Patzek *et al*., is based on linear and Darcy flow of gas, relying on a simple gas production model related to the physics and geometry of unconventional gas extraction process [39]. The simple but technical validation of the analytical model incorporating reservoir conditions makes for easy application by non-technical policy makers and appraisers. Browning *et al*., contends the approach is an integrated bottom up, multidisciplinary study by geologist, engineers and economist [42].

The approach could also be used to account for changes in pressure and reservoir conditions. In addition unlike the LGM, the need to determine a carrying factor dependent on EUR is eliminated. The analytical model can also be considered a hybrid of an empirical model and type curves. The empirical model characteristic is exhibited by its late time exponential decline while its type curve similarity is based on gas Darcy law and linear flow basis. However the validity of this approach is questionable if the empirical conditions (exponential decline) or single phase Darcy flow are not demonstrated by an unconventional reservoir.

Overall this review does not seek to identify a superior approach to shale gas production analysis and estimation that works best in all contexts but identifies strengths, fundamentals and tradeoffs. The best response to model selection and review pertaining to shale gas production requires method research in relation to model suitability and relevance based on condition. Consequently model evaluation and application could be based on their applicability to undeveloped shale gas fields, ability to account for uncertainty as well as well consideration for reservoir heterogeneity.

Application to Undeveloped Shale Gas Fields

Applying decline and type curves in the appraisal of undeveloped fields requires fitting historical production data sourced from extrapolating analogous developed producing regions. Weijeimars makes a first attempt to evaluate the economics of undeveloped European shale plays (Poland, Austria, Germany, Sweden and Turkey) applying a type curve analysis assuming an exponential decline function and applying an estimated ultimate recovery/well from Kuhn and Umbach’s 2011 study based on various reports and unspecified analysis [20]. Taylor’s report focusing on the United Kingdom shale gas production potential production assumes an average EUR/well from developed US shale plays and an initial production rate [44]. The validity of results based on average EUR/well is highly unlikely. Mc Glade *et al*., notes that extrapolation of production experience is appropriate for developed regions where production is relatively advanced while a bottom up analysis of geological parameters seems acceptable for undeveloped regions [8].

The rate transient analysis based model developed by Patzek *et al*., relies on the physics of drained fractured, low permeability shale driven by geological characteristics [39]. Applying rate transient analysis in undeveloped shale plays requires the estimation of some or all of the required geological and reservoir parameters due to limited data availability. However the estimation process introduces uncertainties in parameter values and the need to account for these in modeling approaches.

Accounting for Uncertainty

Petroleum reservoirs are complex heterogeneous geological systems, thus characterizing the reservoir is difficult due to uncertainty and nonlinearity in reservoir parameters. Gulen *et al*., conducts sensitivity analysis on the impact of gas price, capital expenditure, taxes, discount and inflation rate to the commercial viability of the Barnet shale play [41]. Weijermars applies a Monte Carlo simulation to calculate the sensitivity of the commercial viability in relation to well productivity [20]. As revealed in Table-2, most studies do not directly consider the uncertainty in the reservoir conditions (below ground risk). Most of the economic assessments focus on above ground risks; gas prices, fiscal regimes and costs. Although above ground risk are important, a comprehensive analysis should also incorporate below ground risks. The geology and reservoir characteristics are main source of uncertainty in unconventional gas reservoirs which impact production. Many authors propose probabilistic Monte Carlo simulation to address uncertainties in reservoir properties [45-49]. Andrews; Monaghan apply stochastic approaches to resource estimates in the United Kingdom [50-52].

Furthermore in relation to recoverable resources, parameter correlations exist between the reservoir properties; perhaps parameter relationships could be established based on data availability. Clarkson *et al*., provides common data and analytical sources for key unconventional gas reservoir, fluid and rock properties [53].

The option of using a decline curve requires applying decline trends analogues from one basin to another and assumes either an exponential or hyperbolic decline. Wejeimars [20] applies a decline curve analysis assuming an exponential decline function while Taylor applies a hyperbolic curve with a decline factor of 0.8436 [44]. Although Wiiliam-Kovacs and Clarkson apply a stochastic method in prospect screening using a modified Wattenbarger procedure, uncertainty remains regarding analog production data selection and fracture properties [54].

Clarkson *et al*., notes that the primary advantage possessed by analytical methods over decline curves is the ability to produce a distribution of forecast based on uncertainties of key reservoir properties [21]. Applying an analytical solution that honors the physics of gas flow avoids the debate surrounding hyperbolic or exponential decline as well as decline factors; Anderson *et al*., offers case studies with a rate transient analysis [55]. Felgueroso-Cueto and Juanes confirms Patek *et al*.,'s contribution in reducing uncertainty and unraveling the physics of gas recovery from shale rocks [40, 39].

Accounting for Heterogeneity

Unique reservoir properties along with completion and simulation style have a profound impact on the type and sequence of flow regimes and thus methods used in analysis [21]. Mc Glade *et al*., conclude historical production data reveals empirical evidence that shale productivity varies within and between shale gas plays [8]. The US Energy Information Administration (USEIA) in a 2013 report notes that shale formations in the US have displayed heterogeneous geophysical characteristics with variance occurring within 1,000 feet or less. Cipolla and Ganguly attribute the heterogeneity to source rock diversity [56]. Kaiser suggests the EUR estimation is determined by petrophysical factors as well as the success of the fractured network in shale gas wells [12]. Gulen *et al.*, supports the heterogeneous hypothesis by proposing economic evaluation of shale gas basin applying individual well production and economics to the Barnet shale play while Gulen *et al*., applies a similar approach to the Fayetteville play [41, 42]. Although Nobahkt considers completion heterogeneity, reviewed decline and type curves do not consider reservoir geophysical diversity [34]. Weijermars applies the decline curve method to entire basins located in different countries a debatable approach [20].

CONSEQUENCES AND CONCLUSION

This review summarizes the basis and identifies the limitations of models applied in unconventional gas production analysis and estimation. The methodology applied depends on the researchers aim, objectives and data access to applicable parameters. Overall the methodologies and approaches applied in analyzing as well as forecasting production from unconventional gas wells are evolving. Most economists interested in the analysis and forecast of production from unconventional gas wells need a basic understanding of the theories guiding various models.

This study probes the impact and applicability of various assumptions guiding the reviewed production analysis and estimation models. Consequently, the review conclude that production analysis and estimation of undeveloped unconventional gas reservoirs based on type curves and numerical models present flaws that make them impractical for economic analysis of undeveloped unconventional wells. The impracticality results from the absence of production and drilling data which could be used to develop decline and type curves usually based on initial production rates. The option of applying analytical methods also presents challenges in terms of data availability. Analytical methods are dependent on rock and reservoir parameters. However source rock geological parameters are often not publicly available; under United Kingdom onshore license terms, well data available to regulators are confidential for four to five years [50].

Although a lot of research currently focuses on unconventional gas production analysis and forecast, gaps remain in terms of undeveloped shale play recoverable reserve forecast. As a result most regions contemplating developing gas resources do not apply appropriate recoverable reserve methods. This further affects the ability to justify investment, energy security contributions and design of robust regulatory regimes to support shale gas development if sustainable. Recoverable resource forecasts impact both the economics and sustainability criteria of shale gas plays which could be aided by the application of an appropriate production estimation method.

Additionally, accounting for uncertainty in below ground parameters have been less analyzed with more focus on above ground risks. The need exists to extend current forecast methods to account for reservoir risks due to reservoir heterogeneity. In addition the extended method could be applied to undeveloped shale gas plays where uncertainty surrounding reservoir data and rock properties are more pronounced. Analytical method application to undeveloped shale plays could be enhanced by introducing stochastic and correlation analysis. Clarkson proposes production forecast leading to reserve booking should be modeled applying an analytical method [21]. Although analytical models seem better positioned to be further developed for appraising undeveloped shale plays due to the ability of the method to avoid extrapolation, significant research has to be conducted to address the identified limitations and ensure sustainable shale gas development if commercially viable.

Abbreviations

CBM	Coal Bed Methane
EUR	Estimated Ultimate Recovery
SEPD	Stretched Exponential Production Decline
PLE	Power Law Equation
LGM	Logistic Growth Method
Mscf	Million Standard Cubic Feet
REI	Rock Extractive Index

Field Variables

B_g	Gas formation volume factor, ft^3/scf
b	Decline parameter
q/ q_t	Production rate/ well flow rate
q_0/ q_i	Initial gas flow rate
q_1	PLE Rate intercept
D^{θ}	Decline constant
K	Carrying capacity
r	Model random number
f_n	Scatter level
k	Rock permeability
θ	Rock porosity
c	Compressibility
A_f	Area of exposed Rock
µ	Viscosity
Δp	Change in Pressure
a	LGM Constant
n	Decline exponent (Hyperbolic and Exponential)
t	Time (days)
Ʈ	SEPD Characteristic time parameter

Dimensionless Variables

n	SEPD Exponential parameter
b_{Dpss}	Pseudo Steady state parameter
q_{Dd}	Dimensionless decline rate
t_{Dd}	Dimesionless decline time
t_{DA}	Dimensionless time
q_D	Dimensionless rate

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