

How much Natural Gas is there? Depletion Risks and Supply Security Modelling

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Natural Gas Depletion Risks and Supply Security

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Abstract

Natural gas supply security and depletion risks highlight a parallel framework similar to crude oil evolution in extraction and consumption. We model this process at a global level. A local comparison is introduced with reference to Former Soviet Union and Italy. Modelling is based on the generalized Bass model (GBM) with special interventions in order to represent and interpret historical large perturbations. The combined use of nonlinear least squares (NLS) and autoregressive moving average with transfer functions of regressive variables (ARMAX) allows a good inference performance starting from British Petroleum (BP) production data. The main results refer to peaks and depletion times estimation under both constant and modified scenario hypotheses.

Key words: Natural gas depletion, Diffusion process, Generalized Bass model, Nonlinear models, Oil depletion, ARMAX

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1 Introduction

- *Resources and Reserves* -

The natural gas abundance assessment at global and regional level is relevant because this resource is *non-renewable*: its formation takes possibly millions of years. Measuring natural gas in the ground is a very difficult purpose because technical, economic, strategic and social viewpoints are partially conflicting or at least not independent from each other.

A great deal of inference and estimation is involved and new technologies are becoming increasingly efficient and reliable. See, for instance, recent advances in producing and measuring techniques, Vxmeter, Q-technology by Schlumberger, in Gould *et al.* (2007). Nevertheless, it is a common opinion that no one really knows exactly “how much natural gas is there” until it is extracted. A confirmation of the conflicting interests and corresponding “technical definitions” regarding different typologies in natural gas resources is recognizable by observing the different classifications systems adopted by Energy Information Administration (EIA), International Energy Agency (IEA), Oil and Gas Journal (OGJ), World Oil magazine (WOM), BP Statistical Review of World Energy (BPSR), World Oil and Gas Review (WOeni).

Let us examine, for instance, the EIA’s classification system for natural gas resources. The “Natural Gas Resource Base” (NGRB) is the broadest classification and includes the entire volume of natural gas *contained* and *trapped* in the earth before any extraction. A large part of NGRB is technically non-recoverable with present or near future technologies. In this sense *Conventional natural gas* which may exist in the earth and is trapped in reservoirs is contrasted with *Unconventional natural gas* that takes different forms and is more difficult to extract for a lack of adequate technologies or for too high costs. There are six main categories of unconventional gas: deep natural gas, tight natural gas, Devonian shale gas, coalbed methane, geopressurized zones gas, methane hydrates. The challenge or hope is that as technology advances, the resource potential of unconventional natural gas may be less virtual. The NGRB *Recoverable* resources for which a production technology exists are subdivided into *Discovered* and *Undiscovered Technically Recoverable Resources*. Discovered recoverable resources include up to date production and the gas that remain to be produced, i.e., the “reserves”. *Economically Recoverable Resources* are a subset of previous “reserves” for which there are positive economic returns on the basis of current market conditions. This threshold may vary along time. The “reserves” which are jointly economically recoverable are broken down in two main classes: *proved reserves* and *other reserves*. Proved reserves are estimated with a 90% probability (P90) and their extraction at present conditions is “reasonably certain”. Other reserves are denoted with a

variety of terms: probable reserves, possible reserves, indicated reserves, inferred reserved, etc. and are characterized by different levels in extraction probabilities with a lack of agreement in numeric evaluations (P50, P10, P05, etc.).

Table 1
EIA and NPC compiled estimates

US Natural Gas Technically Recoverable Resources (EIA, 1 Jan 2000, Trillion cubic feet)		US Natural Gas Resources (NPC, 1 Jan 1999, Trillion cubic feet)	
Non associated undiscovered gas	247.71	Old fields	305
Inferred reserves	232.70	New fields	847
Unconventional gas recovery	369.59	Unconventional	428
Associated-dissolved gas	140.89		
Alaskan gas	32.32	Alaskan gas (old fields)	32
Proved reserves	167.41	Proved reserves	167
Total Natural Gas	1190.62	Total Natural Gas	1779

Comparing EIA 1 Jan 2000 compiled estimates and the corresponding ones by National Petroleum Council (NPC) in 1999 for the USA, Table 1 denotes the variability of definitions and estimates regarding natural gas supplies and this is an obvious source of uncertainty so that a “definitive” estimate of the residual economically and technically recoverable natural gas is not clearly recognized.

New technologies such as seismic exploration (onshore and offshore), magnetometric and gravitometric satellite tools, 2-D, 3-D and 4-D seismic imaging, Q-technology allow a better understanding and positioning of possible reserves. Revisions of previous estimates are a common consequence. Historical proved natural gas reserves are in general not changed significantly over past 10–20 years: this may be, to some extent, a surprising fact.

- *Ultimate Recoverable Resource Estimation* -

We consider more convenient an *indirect answer* to the question mentioned above. Our main interest is in the *Ultimate Recoverable Resource* (URR) determination. Following Guseo *et al.* (2007) we may consider NGRB at global or local level as the existing Physical Resource of interest. The corresponding URR for natural gas is only a limited subset of it. Indirect determination of a realistic notion of “reserve” must be algebraically discounted with technological, economic and strategic conditions so that the URR for natural gas is the most relevant quantity of interest, i.e., the “total amount of a finite resource which may be obtained at the end of extraction or production process as a result of all concurring forces”. This avoids unrealistic “reserve” definitions based on purely virtual notions. Historical *production data* summarize the variable joint contributions of technological, economic and social effects, including dynamic learning, on a production of a finite resource. Extraction

data may be interpreted within a *diffusion of innovation* framework under possible exogenous interventions. Natural gas aggregate demand is strongly correlated with the diffusion of the corresponding technologies in transport, heating appliances, electric power generation, chemical reforming, etc.. The common unknown asymptotic *market potential*, expressing the diffusion ceiling or carrying capacity, is replaced by the unknown URR.

An analogous point of view was expressed in Guseo and Dalla Valle (2005) and in Guseo *et al.* (2007) with reference to crude oil. The generalized Bass model (GBM) (see Bass *et al.* (1994)) is the main tool and is combined with an ARMAX framework for the implementation of residual autocorrelated deviations not recoverable with the direct control of a special intervention function that incorporates known and interpretable historical shocks of different origins.

The well-known pioneer of historical forecasting on crude oil depletion is Hubbert (1949). He correctly estimated in 1956 the USA oil peak around 1970 and successively in Hubbert (1962) recognized the equivalence of his model with logistic Verhulst equation (see Verhulst (1838)). More recently, Campbell and Laherrère (1998) published a well-known paper on this topic that influenced and stimulated a variety of research on this theme and related issues. Many successive modelling approaches may be thought as extensions of Hubbert logistic basic model. See, for instance, Reynolds (1999) and Reynolds (2002) for price and cost inclusions, Laherrère (2002) for creaming curves, Laherrère (2003) for multi-Hubbert modelling and Laherrère (2006) for reserves/production analysis. Previous approaches, even if correctly based on production data modelling, are not able to include in the model shocks and strategic, regulatory or technological interventions with flexible and interpretable tools.

The GBM (see Guseo and Dalla Valle (2005), Guseo *et al.* (2007)) generalizes Hubbert's model including interventions and, if combined with appropriate ARMAX sharpening, is a robust and simple method for innovation diffusion modelling and forecasting under selected scenario hypotheses.

The statistical and forecasting literature on URR estimation is quite limited with some important exceptions. Two reviews in this area are those by Adelman and Jacoby (1979) and by Kaufmann (1988). Recent econometric extensions of Hubbert model are provided by Kaufmann (1991), Cleveland and Kaufmann (1991) and Pesaran and Samiei (1995). These extensions are directly based on the logistic Hubbert model for cumulative or rate production (instantaneous) data. There is no attempt to discuss the basic foundations/assumptions of the Hubbert's model. Following Bass terminology this accounts only for *imitative* response of the system not for *innovative* component of the associated diffusion framework. The proposed extensions for

economic, political or technological efforts are not compared with the definition of differential equation (Verhulst's equation modification) which jointly considers logistic diffusion under an exogenous intervention. This intervention may modify solutions so that much of the oscillatory deviations may be induced by a weakly specified model.

More recently, a method in comparing logistic (Hubbert model) with gaussian alternative for USA and world oil data is examined in Bartlett (2000). A general paper on oil depletion by Korpela (2002) gives a wide insight in the area by considering historical aspects, technological and detailed information regarding the oil actors. Modelling is essentially concentrated on standard Hubbert approach. An interesting section is devoted to various aspects of world oil reserves assessments. Peak dates are determined following translated Hubbert curves proposed by Laherrère. The latter approach is not widespread accepted because it deletes the over production during period 1951–1979 without a compensating equation balancing effect. New advances in Hubbert like modelling are provided by Berg and Korte (20076), where they model simultaneously extended Hubbert models by considering equations systems that jointly account for supply–demand or supply–demand and reserves dynamics. Analysis is performed following qualitative differential equation characterization. An omitted aspect is the description of exogenous effects due to political, economic and social interventions. Nevertheless, the inclusion of demand and reserves variables is questionable due to well–known difficulties in availability of reliable information.

The paper is organized as follows. In Section 2 we summarize briefly the technical bases of GBM with the motivations that justify our choice. In Section 3 we study the evolution of world natural gas production. In Sections 4, 5 and 6 we examine three local cases: Former Soviet Union (FSU), Italian and Great Britain natural gas productions. The aim is to evaluate, with comparative scenarios, the relationships among peak times and duration estimates. Section 7 is devoted to final remarks and discussion.

2 GBM diffusion model and statistical aspects

There are different possibilities in diffusion of innovation modelling. Complex System Analysis, CSA, (see, for instance Wolfram (1983), Ganguly *et al.* (2003), Boccara (2004) and Newman (2003), among others) allows a micro foundation basis of aggregate behaviour. Stochastic differential approach or a semi–deterministic differential approach are intimately connected with CSA (see Guseo and Guidolin (2007a) and Guseo and Guidolin (2007b)) and are

more suitable for statistical *aggregate data handling* of an existing life cycle process during its evolution.

A basic differential approach on innovation diffusion modelling is developed by Bass (1969) and his model includes the logistic equation by Verhulst (1838) as a special case and, therefore, the Hubbert model. An extension, the generalized Bass model, GBM, introduced by Bass *et al.* (1994), incorporates exogenous intervention factors that control evolutive dynamics.

The diffusion of innovations in a social system is represented over time by a status change of an adoption unit from the *neutral* state to the *active* state. Within the standard Bass model (see Bass (1969)) the system of potential adopters, or reference population, is decomposed into three sub-populations: *innovators*, *imitators* and *neutrals*. For simplicity reasons we may consider a one-to-one correspondence between single adoption and corresponding adopter. Each sub-population is characterized by a separate share: p , q and respectively, $1 - p - q$. The conditional adoption probability is 1 for innovators, z/m for imitators (word-of-mouth) and 0 for neutrals. The typology of a potential adopter is unknown so that, by a simple marginalization, we obtain the corresponding *hazard ratio*, i.e.,

$$\frac{z'}{m - z} = p \cdot 1 + q \cdot \frac{z}{m} + (1 - p - q) \cdot 0, \quad (1)$$

that describes the adoption probability of a generic unit belonging to the non-adopters group, i.e., the residual market ($m - z$), where m depicts the market potential (or carrying capacity) and z defines the cumulative adoptions (or adopters) at time t . The instantaneous or rate adoptions, z' , in the standard Bass model, BM, are therefore,

$$z' = \left(p + q \frac{z}{m} \right) (m - z) = m \left(p + q \frac{z}{m} \right) \left(1 - \frac{z}{m} \right). \quad (2)$$

The carrying capacity, m , is not exogenously defined. It is simply an unknown parameter of the diffusion process. For example, the market potential is only a subset of a susceptible population of consumers and, by analogy, as we will see in Section 3, natural gas unknown URR is only a subset of the corresponding Physical Resource, NGRB, and is determined by the evolutive pattern of the extraction process.

The rate adoption curve of standard Bass model, $z'(t)$, as a solution of Equation (2), depicts a locally symmetric bell-shaped distribution. This model has been fully confirmed by thousands of applications in quantitative marketing literature with reference to limited life cycle products. Non-renewable resources and, in particular, natural gas, are simply goods, that may be

“adopted” by social system as standard products. Interventions can alter this “baseline” evolution.

The basic Bass model is extended in Bass *et al.* (1994) with the introduction of a general multiplicative perturbation described by an integrable function $x(t)$ representing political, economic and strategic interventions. Its neutral level, $x(t) = 1$, depicts the standard Bass model, BM.

The GBM is then

$$z' = m \left(p + q \frac{z}{m} \right) \left(1 - \frac{z}{m} \right) x(t) = \left(p + q \frac{z}{m} \right) (m - z)x(t), \quad (3)$$

and the general closed form solution is

$$z(t) = m \frac{1 - e^{-(p+q) \int_0^t x(\tau) d\tau}}{1 + \frac{q}{p} e^{-(p+q) \int_0^t x(\tau) d\tau}} = mF(t), \quad 0 \leq t < +\infty. \quad (4)$$

Function $F(t)$ is a modified Riccati distribution function (see Guseo (2004a)). Note that a different m , URR in our case, will not produce different peak-time and different duration. It is a scale parameter.

Function $x(t)$ modifies the geometry of time, and not the carrying capacity, m , or the intrinsic diffusion parameters p and q that are dimensionally independent. It can be easily proved (see Guseo (2004b)) that asymptotic percentages of innovators and imitators are not affected by $x(t)$.

Under the assumption that memory effects have a non-uniform distribution over time, we can model the intervention function $x(t)$ in Equation (3) through some different shocks, for example, rectangular and exponential, i.e.,

$$x(t) = 1 + c_1 I_{t \geq a_1} I_{t \leq d_1} + c_2 e^{b_2(t-a_2)} I_{t \geq a_2}, \quad a_1 < d_1. \quad (5)$$

In the rectangular case (usually regulatory effects), c_1 controls depth and sign of perturbations, a_1 and d_1 define origin and ending points of a locally stationary intervention.

In the exponential case (usually spot interventions with decaying effects), c_2 controls depth and sign of perturbations, b_2 describes effects persistency over time and a_2 denotes the starting time. Note that parameter b_2 is commonly negative if memory is decaying to the stationary position (mean reverting), i.e., $x(t) = 1$. Sometimes it may be positive and this aspect introduces a strong acceleration in the saturation of a life-cycle.

Alternatively, function $x(t)$ may be defined with the implementation of exogenous variables, i.e., price variations, marketing mix variables, regulations, policies, etc., in order to test their effects.

Obviously, the Bass models describe large systems and not special production lines or single small oilfields. Nevertheless, flexibility of GBM is well-known in representing large departures from a unimodal bell-shaped depletion profile. See, for instance, the Great Britain, Norway and Alaska exercises in Guseo and Dalla Valle (2005) for the oil case.

Adoptions may also be anticipated or delayed randomly so that the inclusion of stochastic residual components in model building is quite natural.

A nonlinear regressive specification of a statistical version of a GBM is,

$$y(t) = f(\beta, t) + \varepsilon(t) = z(t) + \varepsilon(t), \quad (6)$$

where the deterministic part $f(\beta, t)$, equal to $z(t)$, is a nonlinear function of the unknown vector of parameters $\beta \in R^k$ partially included in $x(t)$. The component $\varepsilon(t)$ is a stochastic process representing the i.i.d. residual error. The usual regressive assumptions consider $\varepsilon(t)$ as a white noise process, possibly with the further assumption of normality.

Therefore, the estimate $\hat{\beta}$ of β parameters in Equation (6) are determined by a non linear least squares procedure (e.g., Marquardt, Gauss-Newton or other criteria; see, for instance, Seber and Wild (1989)). In a second phase, we examine the estimated residuals of nonlinear regression, i.e.,

$$\hat{\varepsilon} = y(t) - f(\hat{\beta}, t).$$

If residuals do not support the hypothesis of a white noise process it is possible to consider a well-known autoregressive moving average transfer function model (ARMAX), proposed by Box and Jenkins (1976) in order to approximate dynamic relationships between an input x_t and an output z_t .

In ARMAX, or, more generally, in ARIMAX models we can explain variable $z_t = y(t)$ not only with delayed autoregressive (AR) or moving average (MA) components but with the help of a function $g(\cdot)$ of the input controlling variable, possibly with delayed terms, which in our case is directly described by the average behaviour $f(\beta, t)$. More formally, we have

$$\Phi(B)\nabla^d\{y(t) - g[f(\beta, t), \dots, f(\beta, t - k)]\} = \Theta(B)a_t, \quad (7)$$

where $\Phi(B)$ and $\Theta(B)$ are backward polynomial operators of order p and

q , respectively, ∇^d is a difference operator of order d , a_t is a white noise, $a_t \sim WN(0, \sigma^2)$, and $g(\cdot)$ is the transformed regressive component.

Inference in Equation (7) may be performed with a sub-optimal two-steps (or more steps) procedure with some simplifying assumptions. Within the applications described in Sections 3–5, we consider two special cases,

$$\Phi(B)\{y(t) - \alpha f(\beta, t)\} = \Theta(B)a_t, \quad (8)$$

and

$$\Phi(B)\{y(t) - \alpha_1 f(\beta, t) - \alpha_2 f(\beta, t - 2)\} = \Theta(B)a_t. \quad (9)$$

At a first step we estimate the transfer function $f(\hat{\beta}, t)$ within a regressive framework and then, at a second step, we optimize ARMAX models in Equations (8) and (9) conditionally on $\hat{\beta}$. The lack of fit of this step-wise procedure is however quite limited.

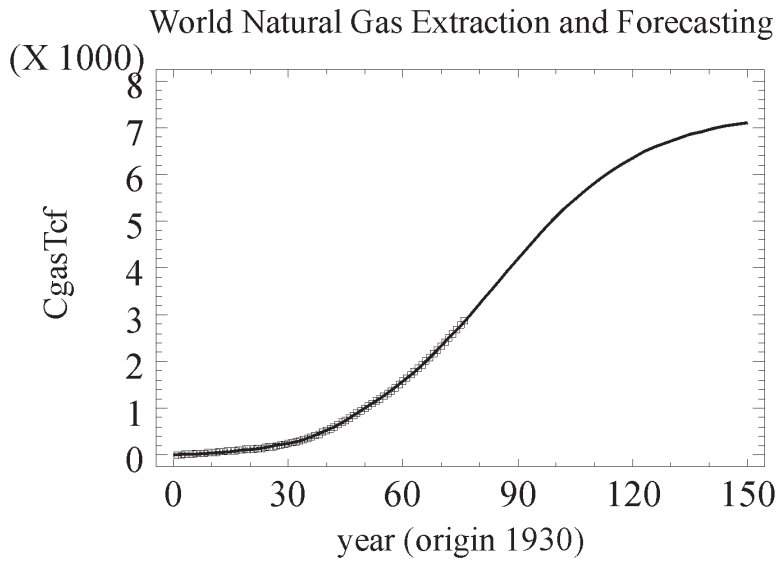


Fig. 1. World natural gas cumulative production: One shock GBM model.

3 World natural gas production evolution

The World natural gas production is examined in detail in order to estimate its aggregate evolution. We consider a time series related to a recent Campbell's study (see Campbell (2002)) which covers the period 1930–2000. Gas data are

expressed in Tcf and depict the annual production. We compare these data with the corresponding ones from the BP Statistical Review (2006) in order to assess possible deviations within the common 1970–2000 time period. Both series are essentially equivalent with minor discrepancies so that we extend Campbell’s series by adding BP’s data concerning 2001–2005 period after a natural transformation from averaged daily BP production data to annual corresponding values.

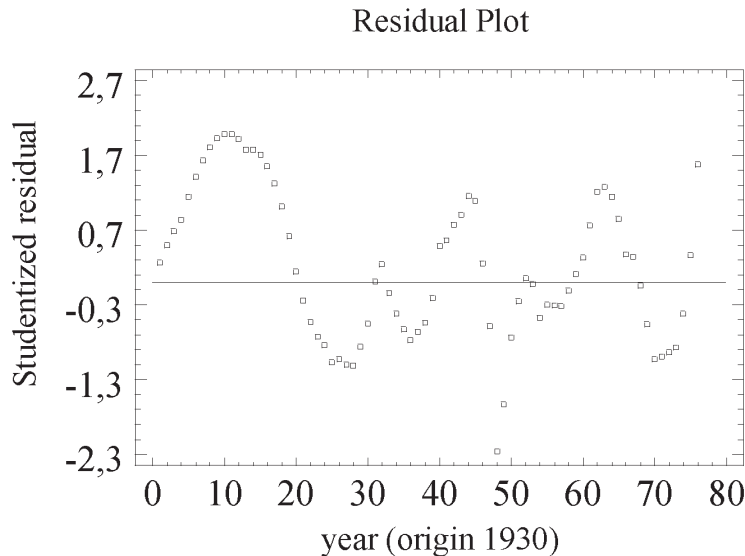


Fig. 2. World Gas Cumulative Production: Studentized residuals in One shock GBM model.

A “parallel evolution” between crude oil and natural gas consumptions may be considered a reasonable hypothesis with some differences related to network externalities. The inspection of instantaneous data production, see Figure 3, confirms a positive systematic increment in natural gas production during the post World War II period, in particular, 1955–75. This is quite natural if we compare this hypothesis with the significant positive and permanent exponential shock originated in 1951 in corresponding world oil data (see Guseo *et al.* (2007)). Nevertheless, the lack of an efficient pipeline network negatively conditioned the extraction of natural gas from deep reservoirs (see Appendix A) and, when discovered in mixed form, it was vented into the atmosphere or burned in place. Current data do not register correctly this extraction especially in the first post World War II period.

Therefore, we consider a GBM with a rectangular shock (*PREgbmr1f05*) properly designed for the absorption of this hypothetical systematic deviation which is strongly correlated with the international changes in life styles after World War II with previously mentioned omission in data registration.

The obtained results are quite satisfactory. See, in particular Table 2.

Table 2

Parameters estimates of World natural gas cumulative production with a GBM under a rectangular shock (*PREgblr1f05*). () marginal linearized asymptotic 95% confidence limits

m	p	q	c_1	a_1	d_1	R^2	$D - W$
7332	0.00048	0.05198	0.3197	31.7	48.3	0.999965	0.1396
(6942)	(0.00046)	(0.05091)	(0.2951)	(30.6)	(47.8)	SSE:	
(7723)	(0.00050)	(0.05306)	(0.3443)	(32.7)	(48.8)	[1882.57]	

Determination index has a particularly high level, $R^2 = 0.999965$. Figure 1 confirms this situation for the estimated cumulative framework. The marginal linearized asymptotic 95% confidence intervals are very small. The ratio $q/p = 108.4$ corresponds (see Guseo (2004b)) to a very limited asymptotic percentage of innovators, $F_p(\infty) = 4.5\%$. The world diffusion (consumption) of natural gas is essentially, even if not exclusive, an imitative process, but less imitative than oil (see Guseo *et al.* (2007)). We note that the supposed high consumption regime is significant and located between year 1962 ($1930 + a_1$) and year 1978 ($1930 + d_1$). The estimated URR is about 7332 Tcf and 90% depletion time is year 2056.

These results are perfectly coherent with the post World War II analysis considered in Guseo *et al.* (2007) where we observe for oil a permanent structural modification in consumption evolution. The 1978 date acts as change-point and it is reasonably correlated with 1979 second negative shock on oil production that was introduced by OPEC in order to optimize returns of supply countries. The limited residuals denote an autocorrelated structure, Durbin-Watson test is very small, $D - W = 0.1396$. This situation is confirmed by Figure 2 where the studentized residuals highlight an evident cyclical pattern.

We apply, as a second step, an ARMAX(2,0,0) representation conditionally on estimated average behaviour at the first step, *PREgblr1f05*, and under an equilibrium hypothesis regarding the intervention function after 2005, i.e., $x(t) = 1$, $t > 2005$. The main results are outlined in Table 3.

Table 3

World natural gas cumulative production. One shock GBM and ARMAX(2,0,0) sharpening. () t -statistic; [] p -values

$AR(1)$	$AR(2)$	<i>PREgblr1f05</i>	$mean$	SSE
1.83265	-0.924146	0.0914463	8.02006	85.05
(32.982)	(-27.1597)	(3.75434)	(2.6492)	{ <i>d.f.</i> 73}
[0.000000]	[0.000000]	[0.000347]	[0.009884]	

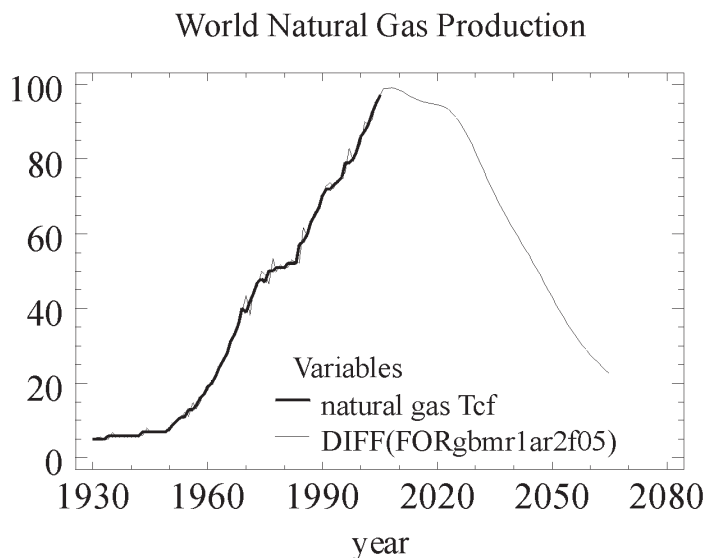


Fig. 3. World natural gas production: One shock GBM model and ARMAX(2,0,0) sharpening.

The proposed ARMAX sharpening is effective. The squared partial correlation coefficient is $\tilde{R}^2 = (1882.57 - 85.05)/1882.57 = 0.9548$ and, in correspondence, the F -ratio, $F = [\tilde{R}^2(N - k)]/[(1 - \tilde{R}^2)s] = [0.9548(76 - 10)]/[(1 - 0.9548)4] = 348.5$, denote a quite significant improvement. Figure 3 represents observed instantaneous annual natural gas data and corresponding ARMAX(2,0,0) modelling (*FORgbmr1ar2f05*): they are essentially equivalent.

If we expand ARMAX representation with a more complex model, i.e., ARMAX(2,0,6) we obtain a similar goodness-of-fit. We omit here for brevity reasons the analysis of variance table. Figure 4 represents both ARMAX models. We note that the more complex model (*FORgbmr1ar2ma6f05*) originates an oscillatory behaviour on the top with a forecasting tail that equates the simpler model. Natural gas peak is then essentially bimodal and positioned (see Figure 5) between 2008 and 2014. The estimated 90% depletion time, under ARMAX(2,0,6) is year 2052. At that date annual production, under ARMAX(2,0,6) sharpening, is estimated about 41.80 Tcf which may be compared with 2005 observed production, 97.20 Tcf.

The supposed substituting effect of new technologies based on natural gas, if compared with Guseo *et al.* (2007) results concerning crude oil, lasts 35 years longer with respect to the 90% time depletion level. The estimated peak date is essentially bimodal, 2008, or few years later, 2014.

This structural difference in oil and natural gas consumption evolution is not surprising and may be explained with reference to technical, economic, strate-

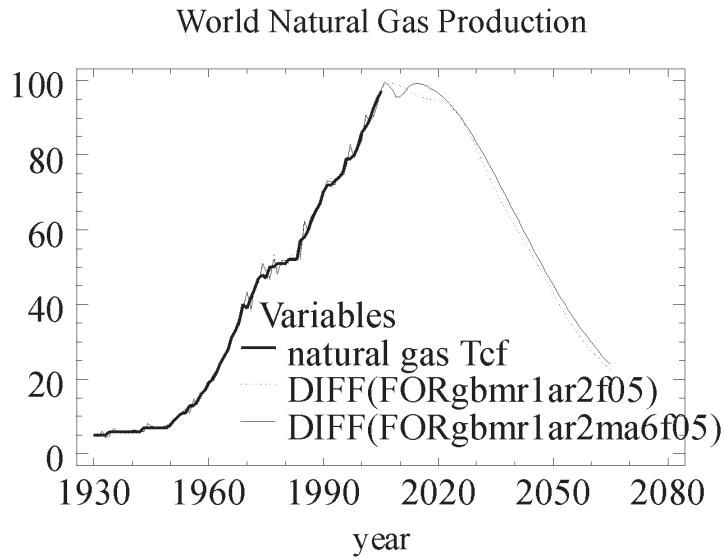


Fig. 4. World natural gas production: One shock GBM model, ARMAX(2,0,0) and ARMAX(2,0,6) sharpening.

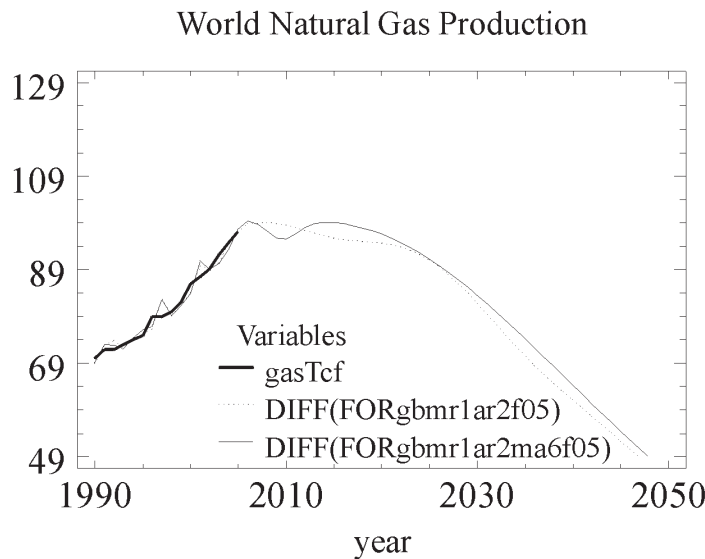


Fig. 5. World Gas Production: One shock GBM model and ARMAX(2,0,6) sharpening (zoom).

gic and social forces that act on these extraction processes. Based on BP 2006 data, we note that international trade movements are about 40% of extracted oil and only 26%, in the natural gas case. The latter is decomposed into two fractions: 74% is transported by pipelines and the remaining part, 26%, is transformed in Liquefied Natural Gas (LNG) and successively shipped

by dedicated LNG ships. These particular constraints have produced and produce today evident network externalities which are well-known in economics, physics and marketing literature (see, for instance, Goldenberg *et al.* (2005), Hauser *et al.* (2006), Srinivasan *et al.* (2004), Shapiro and Varian (1999), Newman (2003)). In this sense a possible further examination of this effect could be performed, by applying special modelling as described, for instance, in Guseo and Guidolin (2007b).

4 Former Soviet Union natural gas production

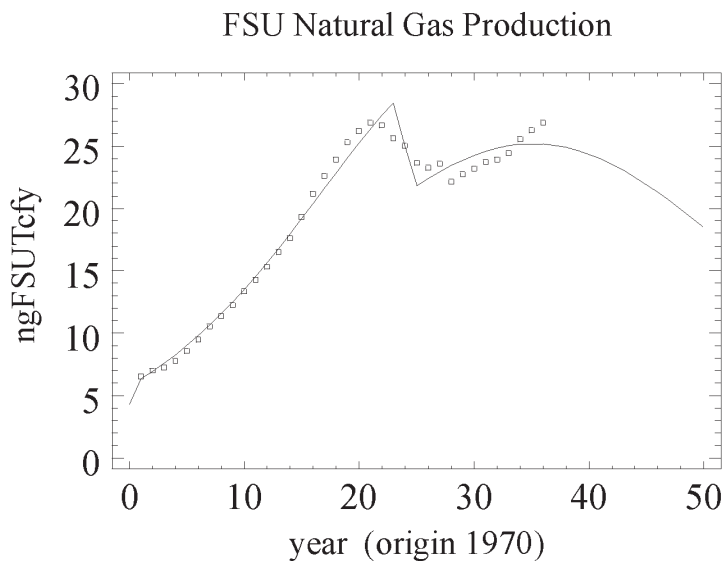


Fig. 6. FSU natural gas production: two exponential shocks GBM model with unknown origin.

It is well-known that the FSU has a world prominent role in present natural gas production and a better positioning with reference to the “proved reserves” in the next decades. If we examine BP Statistical Review 2006 data (see Table 4) we note that 27.5% and 32.4% are the corresponding quantitative values. The natural question is not based on percentage levels but on an assessment of the quality of “proved reserves” estimates. We discuss this point in Section 6. As a preliminary investigation let us consider a specific model for FSU natural gas production.

In this case we have a shorter time series directly based on BP Statistical Review (2006) data that cover only a recent portion of the extraction process, i.e., 1970–2005. If we examine Figure 6 we note that the origin of the extraction process must be estimated with a proper parameter c . At time $t = 1$,

Table 4

World natural gas production and reserves (2005): Large Areas. Source: BP Statistical Review of World Energy (2006)

	Production (2005)		Proved Reserves (end 2005)	
	Tcf	%	Tcf	%
Of which European Union (25)	19.3	7.2	90.8	1.4
OECD	103.5	39.1	527.7	8.3
FSU	73.6	27.5	2058.8	32.4
Other EMEs	89.3	33.4	3761.6	59.3
	266.4	100.0	6348.1	100.0

corresponding to the year 1970, we know only the instantaneous production, i.e., 6.35 Tcf and do not have any direct knowledge of cumulative production till $t = 0$. We suppose that two exponential shocks could be present in the series. A first one with positive effect, c_1 , may explain the strong increasing production during the two decades 1970–1990 and a second one, with negative coefficient, c_2 , that depicts the significant contraction lasted 7–8 years after 1990. A way to solve the problem at a first step is based on a “density estimation”. A very good approximation of Riccati density $f(t) = F'(t)$ is simply

$$f(t) \simeq F(t + 0.5) - F(t - 0.5). \quad (10)$$

In Table 5 we report the results of this first step nonlinear density estimation ($PRED_{basse2t}$).

Table 5

Parameters estimates of FSU natural gas non cumulative production with a GBM under two exponential shocks and a parametric origin ($PRED_{basse2t}$). () marginal linearized asymptotic 95% confidence limits

m	p	q	c	c_1	b_1	a_1	c_2	b_2	a_2
1358.9	0.00036	0.0773	28.97	0.3543	-0.014	0.496	-0.348	-0.025	23.97
(373.9)	(-0.081)	(-0.069)	(-2863)	(-1.85)	(-0.259)	(0.4959)	(-0.646)	(-13.0)	(8.81)
(2344)	(0.082)	(0.224)	(2921)	(2.56)	(0.230)	(0.4961)	(-0.049)	(12.9)	(39.1)

Determination index is good, $R_1^2 = 0.982219$ with $SSE = 29.946$ but a large part of marginal linearized asymptotic 95% confidence intervals are too wide with few exclusions: m , a_1 , c_2 and a_2 . Departures between model and data are rather strong (see Figure 6) and Durbin–Watson statistic, 0.84, denotes prominent residual autocorrelations.

We implement an ARMAX(2,0,0) modelling with a regression component based on previous tentative description, $PRED_{basse2t}$. The corresponding results are summarized in Table 6

We highlight the partially good performance of the combined extended model. The determination index $R_2^2 = 0.9944$ denotes a noticeable corresponding

Table 6

FSU natural gas. Two exponential shocks with unknown origin GBM and ARMAX(2,0,0) sharpening. () t -statistic; [] p -values

$AR(1)$	$AR(2)$	$PREgbmr1f05$	$mean$	SSE
1.49507	-0.596087	0.077714	6.4137	9.48
(10.03)	(-4.81)	(1.92)	(2.65)	{ $d.f.33$ }
[0.000000]	[0.000032]	[0.064]	[0.0125]	$R_2^2 = 0.9944$

squared partial correlation index is $\tilde{R}^2 = (R_2^2 - R_1^2)/(1 - R_1^2) = 0.685$ so that the F -ratio, $F = [\tilde{R}^2(N - k)]/[(1 - \tilde{R}^2)s] = 11.96$ is fully significant denoting the effectiveness of ARMAX extension. Figure 7 gives a good representation of the proposed model. We note the bimodal nature of instantaneous extraction process in 1990 and 2008. After that a smooth declining shape is obtained under an equilibrium hypothesis on intervention function, $x(t) = 1$. URR estimate, 1562 Tcf, is based on forecasts summation from 1970 until year 2056, 1470 Tcf, added to an estimated extraction before year 1970, about 92 Tcf = $(6.35 \cdot 29)/2$.

The 90% depletion time, under ARMAX(2,0,0) sharpening, is year 2035. At that date annual production is estimated about 13.30 Tcf which may be compared with 2005 observed production, 26.864 Tcf.

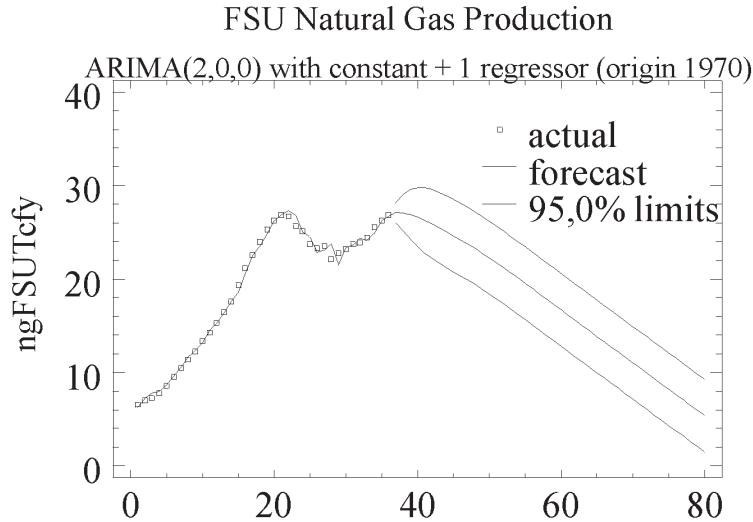


Fig. 7. FSU natural gas production: two exponential shocks GBM model with unknown origin and ARMAX(2,0,0) sharpening.

5 Italian natural gas production

As a third application of our methodology we consider a western state in Europe, Italy, which presents a large dependence on oil and gas supply security with a minor decaying internal natural gas production. Let us consider in Table 7 some basic information derived from BP Statistical Review 2006.

Table 7

Italy: Natural gas and oil Production, Proved reserves, Consumption (2005). Source: BP Statistical Review of World Energy (2006)

ITALY	Production (2005)		Proved Reserves (end 2005)		Consumption (2005)	
	MToe	% (World)	MToe	% (World)	MToe	% (World)
Oil	6.1	0.2	100	0.1	86.3	2.2
n. gas	10.8	0.4	151	0.1	71.1	2.9
n. gas Tcf/y	0.438		5.9		2.77	

Note, in particular, that Italian oil and natural gas consumption is about 10 times greater than internal production in year 2005. Let us consider now internal evolution of Italian natural gas extraction. In this case we have only a short time series in yearly production, based on BP Statistical Review (2006) data, that cover a recent portion of the extraction process, i.e., 1970-2005. We observe a systematic depression in natural gas production extended from 1973 until 1990. We model such local situation with a parametric origin c and with a rectangular depression delimited by a_1 and d_1 extreme dates within a GBM framework. The obtained results under a nonlinear regressive approach are quite satisfactory (see Table 8). We have added Tcf 4.95 to the cumulative BP series, starting from 1970, as an estimate of previous production.

Table 8

Parameters estimates of Italian natural gas cumulative production. GBM with unknown origin and under a rectangular shock. () marginal linearized asymptotic 95% confidence limits

m	p	q	c	c_1	a_1	d_1	R^2	D-W
31.13	0.00379	0.0862	18.75	-0.275	24.6	39.3	0.999919	0.608
(30.26)	(0.00265)	(0.0796)	(16.16)	(-0.302)	(21.6)	(36.6)	$SSE :$	
(31.99)	(0.00494)	(0.0928)	(21.35)	(-0.248)	(27.6)	(42.0)	[0.102645]	

In Figure 8 we can appreciate Italian natural gas cumulative production and its modelling under a shifted origin and one shock included in a GBM model.

The Durbin–Watson statistic, $D - W = 0.608$, suggests the application of an ARMAX sharpening. The preferred solution is based on an ARMAX(3,0,4) with two regressors: the prediction at previous step, $PREbassr1t$, and a lag two delayed prediction, $PREbassr1tm2$. Table 9 summarizes the results with a good SSE , $SSE = 0.03349$.

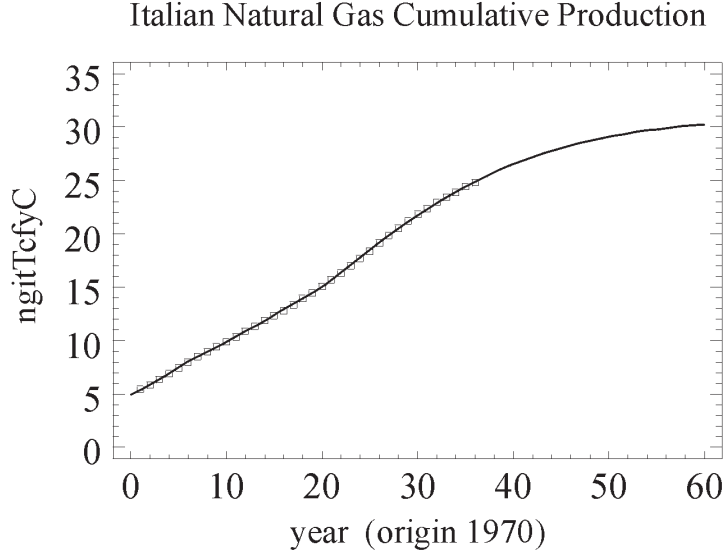


Fig. 8. Italian natural gas cumulative production: One shock GBM model.

Table 9

Parameters estimates of Italian natural gas cumulative production. GBM with unknown origin and under a rectangular shock. An ARMAX(3,0,4) sharpening with two regressors

Parameter	Estimate	t	P-value
<i>AR(1)</i>	0.891313	9.3485	0.000000
<i>AR(2)</i>	0.396363	2.86376	0.007846
<i>AR(3)</i>	-0.301844	-3.67383	0.001000
<i>MA(1)</i>	-1.09112	-9.85707	0.000000
<i>MA(2)</i>	-0.565067	-4.62526	0.000077
<i>MA(3)</i>	0.0711969	0.648951	0.521658
<i>MA(4)</i>	0.327826	10.4166	0,000000
<i>PREbassr1t</i>	0.333831	3.70452	0,000922
<i>PREbassr1tm2</i>	-0.322729	-3.29584	0,002669
<i>Mean</i>	5.4843	33.0176	0,000000

The estimated squared partial correlation coefficient \tilde{R}^2 is particularly high, $\tilde{R}^2 = 0.6737$ and, similarly, the corresponding determination index is $R^2 = 0.999973$. The Italian annual natural gas production, its estimation and forecasting, under an equilibrium hypothesis, $x(t) = 1$, are represented in Figure 9 and confirm a decaying internal production after the observed and estimated peak date, namely 1995. The estimated 90% depletion time is year 2015, under simple GBM, and year 2020, under ARMAX(3,0,4) sharpening. Following the latter model the annual Italian natural gas production in 2020 is about 0.24 Tcf which may be compared with 2005 observed production, 0.44 Tcf.

Italian Natural Gas Production

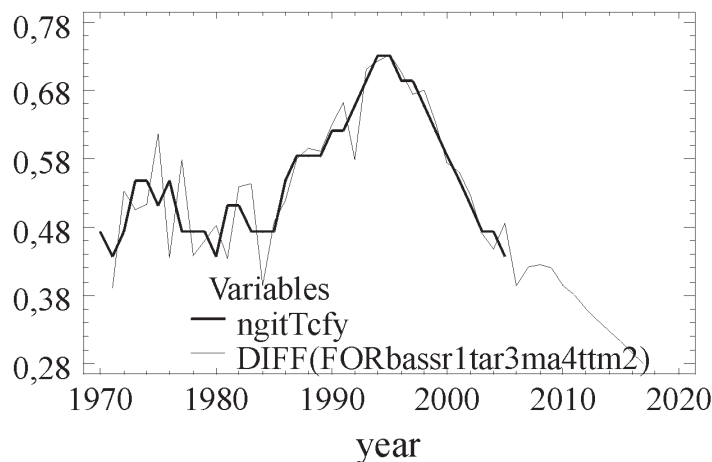


Fig. 9. Italian natural gas production: one shock GBM model with delay and AR-MAX(3,0,4) sharpening.

6 Great Britain natural gas production

A fourth application considers the historical evolution of natural gas production in Great Britain. In Table 10 we present some basic information, based on BP Statistical Review (2006), regarding annual production, proved reserves and consumption related to year 2005.

Table 10

Great Britain: Natural gas and oil Production, Proved reserves, Consumption (2005). Source: BP Statistical Review of World Energy (2006)

GREAT BRITAIN	Production (2005)		Proved Reserves (end 2005)		Consumption (2005)	
	MToe	% (World)	MToe	% (World)	MToe	% (World)
Oil	84.7	2.2	545.6	0.3	82.9	2.2
n. gas	79.2	3.2	477.0	0.3	85.1	3.4
n. gas Tcf/y	3.103		18.709		3.358	

Note that in year 2005 oil production covers exactly internal consumption while natural gas production is 93% of internal consumption. For an estimation of natural gas production evolution we consider annual extraction, in Tcf, based on BP Statistical Review (2006) data from 1970 to 2005. The series has special characters: a large plateau between 1975 and 1992, a subsequent “take-off” starting around 1997 and followed by a peak in year 2000. We try to isolate such systematic deviations with a GBM based on mixed-form interventions. a rectangular one followed by an exponential one. This hypothesis is quite reasonable. “Britain produced flat out at the maximum rate in an ultra free market environment such that production did peak and is now falling at about

10% year” (C.J. Campbell, personal communication).

The obtained results under a NLS approach are quite satisfactory (see, Table 11). Notice that coefficient b_2) of the exponential shock is weakly significant and positive, denoting a permanent not mean-reverting intervention.

Table 11

Parameters estimates of Great Britain natural gas cumulative production. GBM with unknown origin and under a rectangular shock followed by an exponential one. () marginal linearized asymptotic 95% confidence limits

m	p	q	c_1	a_1	d_1	c_2	a_2	b_2	R^2	D-W
90.14	0.00676	0.11556	-0.343	10.0	24.4	0.279	28.2	0.102	0.999951	0.785
(72.13)	(0.00585)	(0.09619)	(-0.386)	(9.4)	(23.9)	(0.196)	(27.9)	(-0.094)	$SSE :$	
(108.14)	(0.00767)	(0.13493)	(-0.301)	(10.6)	(24.8)	(0.361)	(29.7)	(0.299)	[0.824221]	

The Durbin-Watson statistic, $D-W = 0.785$, suggests the application of an ARMAX improvement. The preferred solution is based on an ARMAX(3,0,4) with a regressor, i.e., the first step predicted values with the above mentioned GBM. Its deviance is $SSE = 0.239282$ so that the proposed extension is significant. In fact, the squared multiple partial correlation is $\tilde{R}^2 = 0.7096$ and the corresponding F -ratio is $F = 6.10$.

The Great Britain annual natural gas production, its estimation under a GBM and forecasting values under an equilibrium hypothesis, $x(t) = 1$, are plotted in Figure 10. We notice the above mentioned plateau and exponential take-off as significant strategic interventions and the observed peak date in year 2000 is confirmed. Under previous scenario hypothesis, $x(t) = 1$, the 90% depletion time is positioned in the second half of year 2012, $t_{0.90} = 2011.6$. The corresponding annual production is similar to the rate production during the initial plateau period, i.e., $z'(t_{0.90}) = 1.4$ Tcf.

7 Final remarks and discussion

Final remarks and discussion are organized in three thematic groups: 1) criticism on long-range forecasting; 2) comparison of current results with BP information; 3) FSU estimated reserves deviations and correlated interpretations.

A *first focal point* in this discussion is related to expressed criticism in long-range forecasting. Exemplary papers are proposed by Lynch (2002) and Lynch (2003) even if much of his effort is dedicated to naive versions of Hubbert logistic model. More detailed and documented is a paper by Smil (2000) even if pessimism in scientific work is only a tool for conditional selection of competing theories not a theory in itself. He suggests that “what is immensely more difficult is to anticipate the more likely realities arising from a mix of

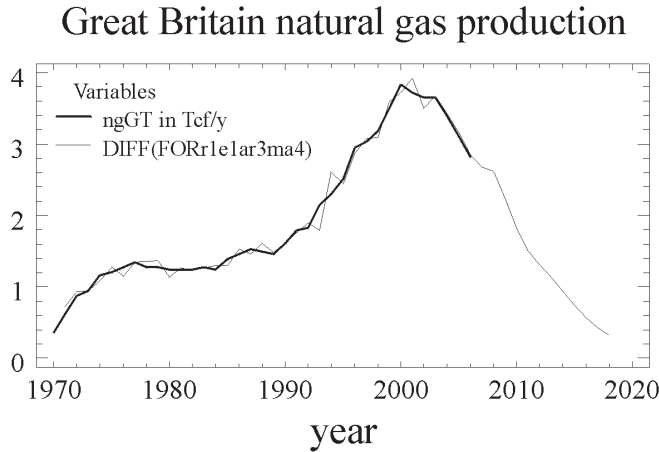


Fig. 10. Great Britain natural gas production: wo mexed shocks GBM and AR-MAX(3,0,4) improvement.

well-understood and almost inevitable continua on one hand and of astounding discontinuities and surprises on the other”. But this correct evaluation does not imply (*non sequitur*) “that we should abandon detailed quantitative point forecast in favor of the decision analysis or contingency planning under a range of alternative scenarios”. In our simple and flexible approach based on a GBM with, possibly, an ARMAX modelling there is a partial and feasible answer to this issue. Intervention function $x(t)$ is historically known and must contribute to the identification and estimation of observed perturbed diffusion of innovation processes. The future is essentially “free” within certain limits and then we can explore, conditionally on some scenario hypotheses, specific forecasts.

A *second aspect* refers to the obtained results and to the corresponding interpretations. In Table 12 we summarize our estimates for each geographic area in order to allow a comparative comment with reference to BP estimated reserves.

We have motivated in the introductory Section 1 why the currently published assessments about “proved reserves” deserve attention. We observe large uncertainties even if measurement technologies are much more precise today. Underground resource measurement is not only affected by natural errors. Political, economic and social interactions are combined with technical aspects so that “reserves” must be estimated on the basis of a realistic URR determination. If we compare BP world “proved reserves”, 6348 Tcf, with our estimated URR-dependent reserves, 4459 Tcf, we note a “reasonable reduction” based on the good properties of our data-driven “learning process”. The estimated

Table 12

Parameters estimates of FSU, Italian, Great Britain and World natural gas production. A comparison with British Petroleum estimated reserves

2005	Current Model Assessments				BP Information			
	FSU	Italy	GB	World	FSU	Italy	GB	World
URR Tcf	1562	31.1	90.1	7332				
Extracted Tcf	782	24.88	72.9	2873				
Reserves Tcf	780	6.2	17.2	4459	2059	5.9	18.7	6348
Annual Prod. Tcf	26.86	0.44	3.10	97.20	26.86	0.44	3.10	97.20
Est. ARMAX Prod. in $t_{0.90}$ Tcf	13.30	0.24	1.4	41.80				
$t_{0.90}$ GBM		2015	2012	2056				
$t_{0.90}$ ARMAX	2035	2020	2012	2052				

90% depletion time at global level under ARMAX representation is year 2052 with a large reduction in annual production, 97.20 Tcf in 2005 vs. 41.80 Tcf in 2052.

A further comparison with mean USGS assessment of oil and gas (2000) is not so easy for various aspects. Natural gas “Cumulative production”, 1752 Tcf, and “Remaining reserves”, 4793 Tcf, refer to estimates from Petroconsultants (1996) and NRG Associates (1995). Their sum, 6545 Tcf, lower than our URR estimate, 7332 Tcf, is then expanded by USGS with “Undiscovered conventional”, 5196 Tcf, and “Reserve growth (conventional)”, 3660 Tcf. Our evaluation, based on GBM evolutionary model, underestimate prudently “Reserve growth” and “Undiscovered conventional” that refer to uncertain possible resources.

A similar and probably more optimistic vision than that stemming from USGS is sustained by Peter Odell who sees natural gas dominating the global supply during the second half of the 21st century by including the “stunning magnitudes of non-conventional gas resources”. His analysis (see, for instance, Odell (2006)) on long-term evolution of the globe energy industry is surely interesting even if, unfortunately, quantitative and modelling aspects are not explicitly documented. He assumes that “any under-achievement in oil and gas production will be the result of a combination of organizational, economic, political and environmental factors” and excludes any physical or technological constraint. But the claimed “Bonanza” assumed in his lucid description is partially contradicted. The recent increasing dependence on speculative trading exchanges and, more precisely, the present turmoil induced by state-owned exploration and production companies restrict the role of multinational oil corporations in limited, risky, expensive and technologically complex production areas.

A possible reason is that physical constraints in oil and gas resources are widely perceived today by non-OECD countries.

“In Europa the current obsession for [gas markets] liberalization will be inevitably abandoned, as producers wisely insist on long-term contracts to ensure security of demand in the context of importing nations’ search for security of supply” (see, Odell (2006)).

But the problem is that long-term contracts to ensure security of demand under anticipated wide investments of Western countries in Eastern economies do not prove a long-term security of supply.

Great Britain was in equilibrium for a long time. See, for instance, Table 10. With reference to reserves estimates in 2005 we notice in Table 12 a quite equivalent level, 18.7 Tcf for BP and, respectively, 17.2 Tcf following a GBM. The estimated 90% depletion time under an ARMAX improvement is year 2012 with a rapid reduction in annual production, 3.10 Tcf in 2005 vs. 1.4Tcf in 2012.

With reference to a little producer, Italy, we note that reserves estimates in 2005 are quite similar, 5.9 Tcf for BP and, respectively, 6.2 Tcf following a GBM. The estimated 90% depletion time, under an ARMAX sharpening is year 2020 with a similar percentage reduction in annual production, 0.44 Tcf in 2005 vs. 0.24 Tcf in 2020.

The most surprising “disagreement” between BP “proved reserves” and our URR-dependent reserves is represented by FSU. BP claimed “proved reserves” are, at the end of 2005, 2059 Tcf, while our model is very “parsimonious”, 780 Tcf. We try to explain such a divergence below. We observe that 90% depletion time under ARMAX representation is year 2035 with a common percentage reduction in annual production, i.e., 26.86 Tcf in 2005 vs. 13.30 Tcf in 2035. In order to evaluate properly previously cited depletion times with corresponding estimated annual natural gas productions, we have to remind that such forecasted values are determined under GBM-ARMAX modelling and, in particular, under an equilibrium hypothesis in intervention function $x(t)$ after year 2005, i.e., $x(t) = 1$. The world and local enormous demand pressure may certainly shrink these conditional, equilibrated scenario, evaluations.

A *third remark* is related to a brief discussion of FSU situation in order to interpret previously mentioned disagreement in “reserves” assessments.

The collapse of the Soviet Union dates back to the late 1980s even if formal dissolution refers to December 1991 (Belavezha Accords) with Gorbachev’s resignation (25 Dec 1991).

In 1993 Rosneft was founded and was an insignificant company operating in small oil fields till few years ago. Russia lost much of its global clout with

the dissolution of the Soviet Union (after 1990). But after successfully reversing a production slump in the early 1990s, it has re-emerged as an energy superpower. This is an explanation of large depression in natural gas production after 1990 (see, for instance, Figure 6). In 2004 Kremlin broke up his oil company, Yukos. Rosneft nominally acquired Yukos assets from an unknown finance company whose address was a café in the city of Tver (see, for instance, Gumbel (2006a)). Russia has large needs of Western capital and there is some hypocrisy in Western fears about Russia's energy sector.

European countries have signed gas contracts with the Russians. For instance, France until 2015 and, more recently, Italy until 2035. "But what happens thereafter that is surely unclear". The natural question is to what extent such contracts (for Italy, France, Germany, etc.) define a realistic basis for gas supply security (in particular for Italy) in the following years. European energy demand is raising while Russia, for its part, needs Western capital if it is to continue rising its oil and gas production (see Gumbel (2006a)).

The second natural question is about the reliability of claimed "proved reserves" which constitute certain guarantees offered as security of capital investments. The pipelines business is an important driver. The Europeans behaviour is contradictory. E.U. governments wants to make energy policy *themselves* and not under the European Commission external energy policy. There are some excellent exclusions, e.g., Poland. Former Chancellor Gerard Schroeder, head of supervisory board between Gazprom (the monopolistic owner of Russian natural gas) and two German firms, is involved in a new underwater Russia-Germany pipeline that avoids to pass through Poland. At the same time, Transneft (the monopolistic Russian pipelines owner) acquired a Russian stake in Caspian Pipeline Consortium (CPC) with Kazakhstan and Oman. More recently, "the Anglo Dutch oil firm Shell bowed to pressure to let Gazprom gain control of \$ 20 billion natural gas project in Sakhalin Island, shocking foreign investors" (see Gumbel (2006b)).

Were Russian proved reserves artificially raised? This remains an open question.

APPENDIX A

Natural Gas: Definitions, origins and historic aspects

- *Nomenclature* -

Natural gas is one of the cleanest, efficient and safest energy sources and it has

a variety of uses in industry, agriculture, transport and heating. It is normally associated with oil reservoirs underneath the earth or in deeper deposits when it stands alone. In its pure form it is colorless and odorless with a high energy density. Unlike other fossil fuels, natural gas combustion emissions are quite limited with low impact on health and environment. Natural gas is a mixture of hydrocarbon gases: methane (CH_4) 80 – 95%, ethane (C_2H_6) 5 – 15%, propane (C_3H_8) and butane (C_4H_{10}) < 5%. In its natural or *wet* form it contains low fractions or traces of rare gases like Helium, Argon, Xenon, Neon and Carbon dioxide, Nitrogen, Hydrogen sulphide and other residuals (water, sand, etc.). The *dry* version is essentially pure methane and is obtained with special separating processes that remove heavier hydrocarbons, rare gases, water, sand and other residuals. The clean natural gas is transported through a network of pipelines of large diameter and then, after appropriate pressure standardization, it is delivered to the points of use through small diameter local networks. Natural gas can be measured in volumetric or thermal units. Production industry normally measures natural gas in billions of cubic feet (bcf) or trillion of cubic feet (Tcf). In Europe a common measure is in billions of cubic meters (bcm): 1 bcm corresponds to 35.3 bcf. As a source of energy, natural gas is commonly measured in British thermal units (Btu): a cubic foot corresponds to 1027 Btus.

- *Origins* -

There are different theories on the origin of fossil fuels in general.

The most widely accepted for natural gas origin is the *thermogenic methane theory* which is directly related to crude oil formation. The organic matter, microorganisms, plants, animals, etc. lived millions of years ago was combined with mud, sediments and compressed under crustal movements. Compression and high temperatures underneath the earth broke down the carbon bonds in the organic matter. At low temperatures crude oil were the common outcome of such transformations. With an increasing depth the corresponding higher temperatures originated more natural gas. Mixed natural gas and oil reservoirs are located 1 to 3 kilometers under the earth crust. Deeper underground deposits normally contain natural gas and sometimes pure methane.

A different theory, the *biogenic methane theory*, is based upon the anaerobic transformations of organic matter by microorganisms near the earth's surface. Under rare circumstances this methane, normally dispersed into the atmosphere, could had been trapped underground by crustal movements. A well-known current biogenic methane production is landfill gas.

A third theory regarding methane formation is *abiogenic* in nature and is not widely accepted. It is based on the combination of hydrogen-rich gases with

carbon molecules in the absence of oxygen at a high depth under the earth's crust. These combined gases move towards the surface of the earth forming methane deposits in reservoir sites.

The most relevant differences among the previous theories refer to time origin of the natural gas formation, to the localization and to the physical extension. The *thermogenic methane theory* does not exclude present new formation of methane but in mankind time interval these contributions are irrelevant as compared with the originating bio-physical processes dated millions of years ago. This is the reason why natural gas, like other fossil fuels, is considered as a non-renewable resource.

- *Trapped natural gas* -

Most of the natural gas rose (and rises today) to the earth surface and dissipated into the atmosphere. A limited deal rose up into special geological formations characterized by layers of porous sedimentary rocks covered by an impermeable layer of denser rocks. These special geological formations, *anticlinal formations*, trapped natural gas and oil under the ground as their extent is sufficiently large. They constitute reservoirs that may be technically and economically exploited. Extraction of natural gas is based on drilling rigs plants that allow the release of natural gas and, possibly, of oil under natural or artificial pressure. We do not describe here “unconventional” formation of natural gas deposits.

- *A brief history* -

Natural gas first historical track is recognized in the ancient Greece on Mount Parnassus in about 1000 B.C., where an astonishing *burning spring* rising from a fissure in the rock was interpreted as a sign of the divinity. A temple in this site housed a priestess known as the Delphi Oracle. Claimed prophecies were inspired by the flame. Five centuries later, in about 500 B.C., the Chinese discovered a way to transport natural gas with bamboo canes from fissures in the earth. It was used to obtain drinkable water and salt from sea water by a boiling process. Britain commercialized “natural gas” (coal gas) around 1785 to light houses. In 1821 William Hart dug the first gas well in Fredonia, New York (27 feet under the surface of the earth), and successively formed the Fredonia Gas Light Company which is the first American gas company. In 1859 “Colonel” Edwin Drake dug the first oil and natural gas well at 69 feet under the surface level. During the 19th century, natural gas prominent use was lighting and, at the end of the century, with the diffusion of electricity, natural gas lights were substituted by electric bulbs.

The natural bottle-neck that limited a rapid diffusion of natural gas for heat-

ing, cooking and industrial transformations was the absence of an efficient pipeline infrastructure.

In 1885, Robert Bunsen invented a special burner (Bunsen burner) that allowed a controllable mixed proportion between natural gas and air for a safety flame use. This invention opened a new way to the use of natural gas in America and anywhere in the world.

The lack of an efficient pipeline network before World War II negatively conditioned the extraction of natural gas when formed alone and, when discovered in mixed form with oil (or coal), was vented into the atmosphere or directly burned in place.

In this period the use of natural gas for transport was limited in general with some exceptions, for instance, in Italy.

Pipeline infrastructure started in 1920 but the effective *take off* is situated after the World War II when new metallurgical advances and new welding techniques allowed the construction of reliable pipelines. The pipelines boom lasted into the 60's in America and some decade later in Europe. The new situation allowed the diffusion, with large scale efforts, of new heating appliances, water heaters, boilers, oven ranges. Industry introduced natural gas in manufacturing and processing plants. In particular, a large diffusion of gas turbine emerged in electricity generation. More recently the diffusion of methane in transport is increasing even if petrochemical industry and governments gave incentives for the commercialization of an heavier fuel, the liquified propane gas, LPG, by constructing, for instance, a good network in Europe.

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