Technological Forecasting & Social Change 81 (2014) 143–153

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage:

Diffusion of nuclear energy in some developing countries

Alessandra Dalla Valle, Claudia Furlan *

Department of Statistical Sciences, University of Padua, Padua, Italy

A R T I C L E I N F O

Article history:
Received 17 October 2012
Received in revised form 20 March 2013
Accepted 25 April 2013
Available online 23 May 2013

Keywords:
Diffusion models
Bass models
Nuclear energy
Reactors
Developing countries

A B S T R A C T

Electric power demand is increasing worldwide and, in the last years, energy policy has focused on expanding nuclear power, especially in developing countries. One of the key points surrounding this issue is the depletion time of uranium; further, forecasters had estimated that the use of nuclear reactors would come to a halt in 2020 by IAEA. It is apparent that we can no longer sustain the evolutionary model of energy consumption typical of the last century. The Fukushima disaster of 2011 reopened the debate about the use of nuclear energy to produce electricity. Japan, Switzerland and Germany decided to halt new nuclear projects. However, the question remains: would the world's uranium resources suffice to meet nuclear energy projects, especially those slated in the developing countries? This paper offers an analysis of nuclear energy diffusion of some graduated developing countries (the Slovak Republic and South Korea) and some developing countries (Ukraine, China, Bulgaria, and India); moreover, it estimates the depletion time of uranium using a Generalized Bass model and OECD forecasts, with the uranium requirements scheduled for 2035. This study concludes that, given the estimated depletion time of uranium, and considering 50 years as a reasonable lifetime for reactors, the present international nuclear energy policy, and in particular the nuclear projects of the developing countries are not sustainable.

1. Introduction

The diffusion of a life-style model that proposes western development in countries such as China and India, offers one of the reasons for the increase in the world's energy demand.

One of the most difficult challenges of the future will be to maintain a balance between energy demand for economic and social progress and the consequent environmental and social–political impacts deriving from this demand. Direct signals include, for instance, atmospheric changes, sweltering summers, and geological disasters that happen with unusual frequency.

The present economic system essentially grounded on energy deriving from fossil fuels, which strongly contributed to the greenhouse effect, now faces its imminent depletion era. To this end, nuclear energy offers one possible answer as a CO_2-free, safe, and cheap solution to the world's energy problems [1]. Starting in 1950, we can identify at least two important periods of nuclear energy expansion: the years from the 1980's to the 1990's, and from the 1990's to today. The first period shows a slowing down due to different factors, such as the fall of fossil fuel prices in 1983, the liberalization of the energy market first in the United States and then in Europe, and the accidents of Three Mile Island in 1979 and of Chernobyl in 1986. The second period, on the other hand, represents a sort of nuclear renaissance, but it came to a screeching halt after the Fukushima Dai-Ichi accident in March of 2011.

Governments worldwide are revising their nuclear policies in reaction to the Fukushima Dai-Ichi accident, but not in the same direction or with the same intensity. Some, predominantly developed, countries, like, for example Germany and Switzerland, have decided to gradually phase out the use of nuclear power, by exploiting operational nuclear reactors

* Corresponding author. Tel.: +39 049 827 4129; fax: +39 049 827 4170.
E-mail address: furlan@stat.unipd.it (C. Furlan).

0040-1625/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.techfore.2013.04.019

through their natural life cycles. Notably, relative to the concept of natural life cycle, in 2009 one half of US nuclear plants obtained a life extension license, from 40 to 60 years, by the Nuclear Regulatory Commission; after Fukushima, Germany and Switzerland extended the lifetime of reactors from 40 to 50 years, while Japan extended its to 60 years [2]. Italy, on the other hand, dropped a proposed project to return to the use of nuclear energy. At the same time, the uncomfortable perception of the unavoidability of safety and security questions brings countries, especially developed countries, to naturally invest in the use of renewable resources and new advanced technologies [3], that could lead to solutions, for instance, to the well-known storage problems in this field. On the other hand, developing countries, the principal followers of nuclear expansion before the Fukushima Dai-Ichi accident, are at present more focused on checking the safety of operational reactors, rather than dropping their challenging future nuclear projects.

Developing countries have scarce other opportunities to confront their greatly increasing energy demands, chiefly because of a set of common political and economical backgrounds shared by all these countries. In general, the developing countries lack energy resources for geological reasons and others, such as having experienced wars that have destroyed industrial facilities [4]. Moreover, a lack of private investment money strongly restricts free enterprise leveling off living standards of the populations, as also Mallah [5] highlights in an analysis of energy options in India. In addition, an ever-increasing population density and the presence of weak, uncertain, and naive governments limit the opportunities. These remarks automatically lead us to consider unworkable any clean energy technologies. As a matter of fact Chow et al. [6] remarked that investment in renewable resources requires economical efforts that are not perceived as effective and fully convenient, also considering critical electrical grid conditions. China represents an exception, since it is the world's leading investor in renewable energy technologies and it has become the largest market for wind power; by 2009, China derived over 17% of its energy from renewable sources, most notably from hydroelectric power plants [7]. At the same time, nuclear energy is seen as a reliable, clean (at least in terms of CO_2 emissions), and abundant energy source like no other. China itself has the most challenging nuclear projects in the world (see Subsection 3.3). For South Korea, Lee and Jung [8] compared coal and nuclear as major electricity sources and concluded that the latter offers a unique solution from economic, environmental, and sustainability points of view. Choi et al. [4] see the success of South Korea's nuclear program as a symbol of the planning and organizational skill of a country that has chosen to bet on nuclear power. These considerations are not directly connected to the presence of energy reserves in the region, because they are not necessary for full economic development; in fact many energy-bereft countries have become highly developed and others countries that conversely had substantial reserves still remain among the poorest countries. In this sense, the aspect that seems particularly relevant for energy development of a country is the presence of a well-functioning socio-economic system able to control the energy resources for its full social benefit [6].

The paper first focuses on the expansion of nuclear power demand in those developing countries that now represent the most important supporters of nuclear projects. In particular, we analyze the production of electric power (TWh) coming from operational nuclear reactors of the developing countries of Ukraine, China, Bulgaria, India, and also the graduated developing countries of the Slovak Republic and South Korea, considered developing countries until recently.[1]

Later, this paper discusses the availability of uranium which plays a central role in international nuclear policies. Some countries, such as China, have very challenging projects planned for the near future, all of them depending on uranium availability. Providing an estimate of this latter represents a great challenge itself, such as predicting how long it will last. In fact, reactor technology is focusing on fuel efficiency utilization, but testing nuclear technical progresses is far from easy, due to environmental and worker safety issues. The literature has widely discussed the total amount of uranium available on Earth. At present, forecasts of uranium availability are mainly given by OECD [9] through Reasonably Assured Resources (RAR) and through IDentified Resources (IDR, that is RAR plus Inferred Resources). Based on geological certainties and costs of production, these estimates refer to direct measurements of uranium deposits and sometimes on feasibility studies, with a different degree of confidence between RAR and Inferred Resources.

In this paper, considering uranium as a finite resource [10] and following the theory about diffusion models [11,12], we adopt a quantitative method based upon the Generalized Bass Model (GBM) that uses only world uranium production data (tons) from 1945 to 2009 (source: IAEA PRIS). In this way we avoid the problem of uncertainty based on measurements of reserves and geological resources, which have different degrees of reliability, estimating directly from production data the whole life cycle of uranium, as Guseo et al. [13] did for oil. Moreover, in the GBM, the inclusion of exogenous variables that capture interventions of economic and political nature gives back a more dynamic and flexible model able to interpret the complex factors that contribute to determining the life cycle of energy resources. So, we perform GBM modeling for both the cross-country analyses of the production of electric power (TWh) and the uranium life cycle. We compare GBM estimates with those provided by OECD [9], focusing the debate on the feasibility of the nuclear energy projects of the countries studied for the future. In addition, we discuss the estimate disparities, taking also into account the depletion time of uranium and the growth of uranium requirements as estimated by OECD [9].

The remainder of the paper is structured as follows. Section 2 presents the basics of the GBM; Section 3 shows the diffusion of nuclear energy in the developing countries, and Section 4 exhibits the analysis of the life cycle of uranium, in both cases through GBMs. Section 4 also includes a debate on the feasibility of the nuclear projects, while conclusions are given in Section 5.

2. The model

In this section we present some basic concepts of the Bass model and the GBM, after a brief introduction about other most popular diffusion models. The literature about diffusion

[1] In the following, for brevity, we refer to all of these countries using the term "*developing*" countries.

models starts in the 1960s with the early works of, among others, Fourt and Woodlock [11], Rogers [12], and Bass [14], all of which proposed similar approaches to the theory of the life cycle of a new product or technology on the market. The majority of models still in use were introduced before 1970: later efforts will be principally focused on because to allow more flexibility. Basic growth models that have been extended in different ways include S-shaped curves, such as the Logistic, the Gompertz, and the Bass models. Typical application areas in innovation diffusion are durable goods and technological innovations (see, for instance, Teng et al. [15]).

The Logistic model at the initial stage of growth is approximately exponential; thereafter, the growth slows, and at the end, it stops: typical applications concern the life cycles of personal computers, railroads, air travel, imaging technologies (see, for instance, Libertore and Bream [16]) and so on. The most famous model based on the Logistic curve – in response to Malthus model [17] based on an unlimited exponential curve – was the Verhulst model [18] which, through the addition of a parameter that represents the carrying capacity of the environment, describes the growth of a biological population limited by an upper bound.

In the Gompertz model, the growth is very slow at the beginning and also at the end of the diffusion process. This model is used in particular for the diffusion of mobile phones, the growth of tumors (see, for example, Laird [19]) and especially for all processes in which the initial costs are very high and then slow down at a later stage.

The Logistic, Gompertz, and Bass models have been also compared to one another: Meade and Islam [20], for telecommunications data, conclude that models with few parameters outperform others that are more complex. More recently, Dalla Valle and Furlan [21] showed that the GBM outperforms the Logistic and the Gompertz models, when there are external perturbations that may modify the adoption process.

Nuclear data that we analyze in this paper are particularly influenced by exogenous shocks, like, for example, closure of reactors or connection of new reactors to the grid and strategic decisions by policy makers, such as uranium supply agreements between countries. In the next section we introduce the GBM, its areas of applications, its characteristics and motivations for choosing this type of model.

2.1. The GBM

Innovations and their perception in a social system play a fundamental role in diffusion models. The timing and the interpersonal communication channels among individuals, who have different propensities toward adoption, characterize the growth function shape of an adoption process [22].

Bass [14] introduced the Standard Bass model that differentiates between early adopters, who are influenced by external channels of communications (e.g., advertising, mass media), and later adopters, who are influenced by interpersonal communications (e.g., word-of-mouth). The Bass model has been widely used for its properties and parameters' meaning to model diffusion processes, since it was introduced in several research fields; see, for example, [23–28]. Bass et al. [29] suggested that the GBM outperforms the standard version because it allows the inclusion of marketing-mix variables, which fall under the control of managers; this could aid managers in planning strategic policies [30].

In forecasting diffusion literature, complex models are not necessarily preferred to simpler ones [31], but it is important to use a framework that might include external inputs, especially with limited data [32]. Hardie and Fader [33], for example, mention the possibility of including covariate effects in a GBM, and Kumar and Krishnan [34] propose an application of this method in a multinational diffusion setting. On the other hand, Guseo [35] highlights the extreme flexibility of GBM in including external interventions and proposes an alternative way of including external interventions through special impulse functions, such as exponential and rectangular functions. This latter approach was also followed by Guseo and Dalla Valle [36] and Guseo et al. [13] for oil production; by Guidolin and Mortarino [37] for photovoltaic systems, and by Dalla Valle and Furlan [21] for wind-power systems, both in cross-country evaluations. The GBM was particularly suitable in green energy applications since it allows modeling stationarities and speed adoption variations, which are typical of processes strongly influenced by changes in incentive policies. Recently, Guidolin and Guseo [10] used it in the nuclear energy consumption sector for analyzing, at a world level, uranium extraction, reactor startups, and nuclear energy consumption. Moreover, they also considered some traditional countries that have mostly invested in it (France, Japan, and the USA).

The GBM can be specified in a non-linear regressive framework:

$$w(t) = f(\underline{\beta}, t) + \epsilon(t) = z(t) + \epsilon(t), \tag{1}$$

where $w(t)$ represents the cumulative adoption data, $f(\underline{\beta}, t)$ is the deterministic component specified through cumulative mean functions $z(t)$ of adoption over time, $\underline{\beta}$ is the vector of parameters, and $\epsilon(t)$ is assumed to be a white noise process (or more generally a stationary process). To estimate the parameters of the model, we use a non linear least squares estimation method following the algorithm of Levenberg–Marquardt [38].

The representation of the GBM, introduced by Bass et al. [29], is characterized by the following first-order differential equation:

$$z'(t) = m\left(p + q\frac{z(t)}{m}\right)\left(1 - \frac{z(t)}{m}\right)x(t) \quad \text{for } t \geq 0, \tag{2}$$

where m is the potential market, p and q are the parameters referred to the quota of innovators and imitators, respectively, and $x(t)$ is an integrable function that oscillates around 1. The latter allows the inclusion of exogenous variables that identify interventions of a political and economic nature, which are assumed to have effects on the diffusion process. The general closed form solution of Eq. (2), under $z(0) = 0$ (and $z(t) = 0$ for $t < 0$), is

$$z(t) = m\frac{1 - e^{-(p+q)\int_0^t x(\tau)d\tau}}{1 + \frac{q}{p}e^{-(p+q)\int_0^t x(\tau)d\tau}} \quad 0 \leq t < +\infty. \tag{3}$$

Note that Eq. (2) includes the Standard Bass model for $x(t) = 1$, while for $x(t)$ greater than 1, the adoption process is accelerated over time, and on the contrary, for $x(t)$ smaller than 1, the adoption process is delayed. It is important to note that the intervention function $x(t)$ modifies only adoption time and neither the potential market nor the innovators and imitators parameters p and q.

The intervention function $x(t)$ incorporates exogenous covariates, including, for example, political measures, economic local provisions, and so on.

Guseo [35] proposed a specification of $x(t)$ that was useful for depicting and modeling strategic interventions that significantly modify the diffusion of energy products, e.g., oil and gas. A simple representation of $x(t)$ may be based on one *exponential* shock that identifies a locally intense impulse that progressively loses its effect. The mathematical form of the exponential shock is

$$x(t) = 1 + c_1 e^{b_1(t-a_1)} I_{[t \geq a_1]}, \tag{4}$$

where $I_{[t \geq a_1]}$ is an indicator function assuming value equal to 1 if the shock occurs at time a_1 and value equal to 0 otherwise; so, a_1 coincides with the beginning of the shock, b_1 expresses how rapidly the shock decays toward 0, and c_1 indicates the intensity of the beginning of the shock. If $b_1 < 0$, it means that the shock has been absorbed through time, while if $b_1 > 0$, it means that the shock has not been absorbed yet. The *rectangular* shock is another kind of impulse for intervention function $x(t)$ that identifies a perturbation whose effect stays unchanged over a bounded time interval:

$$x(t) = 1 + c_1 I_{[a_1 \leq t \leq b_1]} \tag{5}$$

where $[a_1, b_1]$ is the close interval in which a shock may occur, while c_1 identifies the intensity of the effect of the exogenous intervention and can assume both positive and negative values. This impulse begins at time, say, a_1 with a given intensity, keeps holding over the interval of length $(b_1 - a_1)$, and then suddenly disappears. A further kind of representation for $x(t)$ pertains to mixtures of different shocks, referring to particular situations in which a series of political interventions, signed at different times, have different effects on diffusion models. The mathematical representation of, for example, two exponential shocks and one rectangular shock is the following:

$$x(t) = 1 + c_1 e^{b_1(t-a_1)} I_{[t \geq a_1]} + c_2 e^{b_2(t-a_2)} I_{[t \geq a_2]} + c_3 I_{[a_3 \leq t \leq b_3]}, \tag{6}$$

where the involved parameters are the same as the preceding examples. It is important to note that Eq. (6) is purely demonstrative and that any combination of impulses both in number and in typology is theoretically possible.

3. Developing countries

The following presents a brief history of nuclear energy and results of the GBMs for each developing country: South Korea, Ukraine, China, Bulgaria, Slovak Republic, and India. The data about both the nuclear energy and the commercial operation state of reactors have been provided by IAEA PRIS. Fig. 1 presents the number of operational, under-construction, and shut-down reactors. Table 1 shows the results of the GBMs and also the goodness-of-fit of the models through the R^2. Fig. 2 shows the cumulative annual nuclear energy (TWh) from 1980 to 2010 and forecasts until 2020 (Ukraine till 2009, and China from 1993).

Among the developing countries, South Korea and Ukraine come first in production of nuclear energy; in the last few years, South Korea has overtaken Ukraine since it has invested much more in nuclear projects. China has not yet reached the level of South Korea and Ukraine, but it is investing more in nuclear energy, and it has more reactors under construction. Bulgaria, the Slovak Republic and India have the same level of production of nuclear energy, even if India, in the last 10 years, has strongly invested in nuclear energy and has 5 reactors under construction as South Korea does.

Fig. 3 shows, for each country, observed and estimated life cycles of nuclear energy (TWh) until 2020.[2] In general, the life cycle of every technology is destined to end. In this particular case, the end of nuclear energy production, using current technology, could happen because of the shutdown of current operational reactors, or because of the replacement of the current reactors with Generation IV reactors (which will have their own life cycle), or for uranium depletion if Generation IV reactors are not implemented in time (see Section 4).

The GBM estimates of life cycles are more reliable when the peak has already been reached. The degree of reliability is discussed country by country.

3.1. South Korea

The history of nuclear energy in South Korea starts in 1972 with the construction of the Kori nuclear power plant. Currently, South Korea has 6 nuclear power plants for a total of 21 operational reactors and 5 reactors under construction. The Koriplant began commercial operation with its first reactor in June 1977, while the Wolsong plant powered up in December 1982, and the Yonggwang plant in March 1986, the Ulchin plant in April 1988, the Shin-Kori plant in August 2010, and the new Shin-Wolsong plant has not yet any reactors connected to the grid.

The proposed GMB for South Korea includes one rectangular and one exponential shock (Eq. (6) without the second exponential shock). The rectangular shock is detected as having a great intensity ($c_3 = 1.9417$) between 1985 ($1980 + a_3$) and 1992 ($1980 + b_3$), and it is explained by the commercial operation of 6 reactors (2 at Kori, 2 at Yonggwang and 2 at Ulchin). The exponential shock was found to be positive ($c_1 = 0.7981$), arising around 1992 ($1980 + a_1$), and its effect is not yet absorbed in time (b_1 is positive). This positive effect is due to the commercial operation of 12 reactors (4 at Yonggwang, 3 at Wolsong, 4 at Ulchin, and 1 at Shin-Kori). The model suggests that South Korea is in the middle of a life cycle and already reached its peak in 2009 (Fig. 3): the plot is essentially characterized by a fast increase up to the present day, and the model predicts a symmetrical decrease in the future. However,

[2] Since annual forecasts come out as the first differences of the cumulative forecasts, the plot starts one year later with respect to Fig. 2.

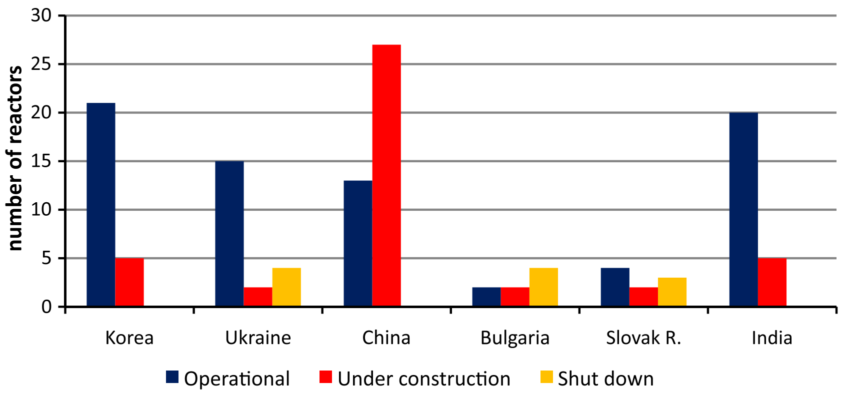

Fig. 1. Number of operational, under-construction, and shut-down reactors in developing countries.

the above forecasts should be evaluated also taking into account that the behavior of the data of the last few years could be interpreted not only as a reversion (as the model catches) but also as a stationarity, waiting for commercial operation of 5 new reactors under construction. In the latter case, we expect a new increase.

3.2. Ukraine

Ukraine has a recent nuclear tradition that goes back to 1970 with the start of site works of the first reactor in the nuclear plant of Chernobyl. At present, Ukraine has 5 nuclear plants for a total of 15 operational, 4 shut-down and 2 under-construction reactors. The Chernobyl plant began commercial operation in September 1977, while the Rovno plant powered up in December 1980, the South Ukraine plant in December 1982, the Zaporozhe plant in December 1984, and the Khmelnitski plant in December 1987.

The proposed GMB for Ukraine includes one rectangular and one exponential shock (Eq. (6) without the second exponential shock). The rectangular shock is detected as having a medium intensity ($c_3 = 0.7684$) between 1984 ($1980 + a_3$) and 1992 ($1980 + b_3$), explained by the commercial operation of 9 reactors (5 at Zaporozhe, 2 at South Ukraine, 1 at Rovno and 1 at Khmelnitski plants), but with the shut-down of 2 reactors in Chernobyl in 1986 and 1991. The exponential shock is negative ($c_1 = -0.2817$), and occurs around 1998/1999 ($1980 + a_1$). The model ensures that its effect has been completely absorbed in time (b_1 is negative). In those years (1997–1999), no other reactors were connected to the grid, and, also in 1999, the first reactor of the Zaporozhe plant made a safe stop for malfunctioning. The constant growth rate of the first shock is

Table 1
Developing countries and uranium world extraction: estimates and asymptotic standard errors (in brackets) for GBMs.

Shock	Par.	S. Korea	Ukraine	China	Bulgaria	Slovak R.	India	Uranium
	m	3932.45	2944.19	1278.72	497.994	426.560	507.137	$3.347 \cdot 10^6$
		(183.013)	(238.897)	(150.376)	91.2463	(11.5816)	(69.1473)	(149809)
	p	0.0010	0.0028	0.0050	0.0147	0.0113	0.0042	0.0008
		(0.0001)	(0.0004)	(0.0004)	(0.0023)	(0.0003)	(0.0003)	(0.0001)
	q	0.0745	0.1223	0.2110	0.1092	0.0258	0.1164	0.0710
		(0.0223)	(0.0044)	(0.0155)	(0.0133)	(0.0018)	(0.0212)	(0.0015)
	a1	11.584	18.3081	10.7451	14.9826	19.3402	9.6396	33.7065
		(0.0428)	(0.3878)	(0.3929)	(0.0519)	(0.3353)	(0.6625)	(0.3548)
exp	b1	0.0070	−0.1172	−1.9533	0.3159	0.0806	−0.1710	−0.4012
		(0.0072)	(0.0884)	(2.9966)	(0.2257)	(0.0115)	(0.1145)	(0.1623)
	c1	0.7981	−0.2817	0.6531	−0.0336	1.7365	−0.4739	0.5353
		(0.4774)	(0.0518)	(0.7597)	(0.0285)	(0.1248)	(0.0935)	(0.1370)
	a2				20.2580		20.5218	46.3548
					(0.4909)		(0.2431)	(0.2645)
exp	b2				0.3039		−0.6199	−0.0564
					(0.2198)		(0.2171)	(0.0187)
	c2				−0.0287		0.9285	0.0408
					(0.0096)		(0.2118)	(0.0024)
	a3	4.8263	3.6194	5.2081	9.8306	4.7261		7.5311
		(0.3846)	(0.7446)	(0.4079)	(0.4052)	(0.1059)		(0.8897)
rect	b3	12	11.6307	9.6648	14.7751	18.9705		18.1604
		(0.1024)	(0.1663)	(0.3073)	(0.38882)	(0.6611)		(0.1453)
	c3	1.9417	0.7684	−0.3420	−0.2517	0.9450		1.6215
		(0.6271)	(0.0635)	(0.0454)	(0.0323)	(0.0472)		(0.0896)
	R^2	0.999985	0.999939	0.999938	0.99995	0.999988	0.999861	0.999944

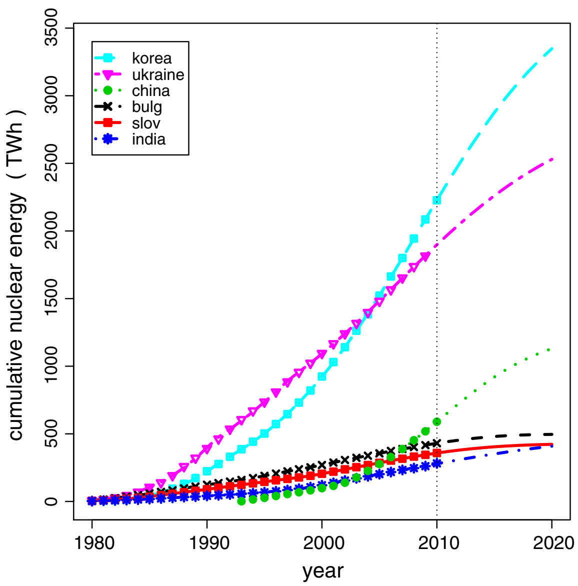

Fig. 2. Observed and predicted cumulative nuclear energy (TWh). Fitted models correspond to GBMs of Table 1 and forecasts go up to 2020.

well identifiable in Fig. 3, and the model suggests that Ukraine has already passed the middle of its life cycle.

3.3. China

China (except Taiwan) has built 4 nuclear plants with 13 operational reactors and 1 reactor under construction. The Qinshan plant started its commercial operation in December 1991, the Guangdong plant in August 1993, the Lingao plant in February 2002, and the Tianwan plant in May 2006. The Chinese nuclear policy is particularly challenging since, at present, another 26 new reactors are under construction, for a total of 9 new plants.

The proposed GMB for China includes one rectangular and one exponential shock (Eq. (6) without the second exponential shock). The rectangular shock is negative for detecting a small intensity ($c_3 = -0.3420$) between 1998 ($1993 + a_3$) and 2002/2003 ($1993 + b_3$). It can be explained as a temporary stop of commercial operation of reactors between the first phase of nuclear expansion with the grid connection of 3 reactors in 1991–1994, and the second phase happened after 2002, with the connection of 10 reactors in 2002–2010 (only 4 in 2002, 2 in Qinshan and 2 in Lingao). Indeed, we can observe this second phase by the exponential shock located around 2004/2005 ($1993 + a_1$), and its effect has been completely absorbed in time (b_1 is negative). Fig. 2 shows how China has had a considerable nuclear expansion rate since the second shock around 2004, and Fig. 3 suggests that it is now in the middle of its life cycle. However, some caution is needed in the belief of the forecasted reversion, since it has not been confirmed by any clear trend of observed reduction in energy production. With the present data, the model seems to end prematurely its life cycle more for its mathematical properties than for the behavior of the data.

China at the moment has not met any problems involving uranium supply issues, since it has its own uranium resources, and it also imports uranium from Kazakhstan, Australia, Canada, Niger, and Namibia. The question remains: can China ensure the uranium supply for the additional 27 reactors under construction?

3.4. Bulgaria

Bulgaria has 2 nuclear plants: Kozloduy, with 6 reactors, of which 4 are in shutdown, and Belene, with 2 reactors under construction. The Kozloduy plant began its commercial operation in 1974 with the grid connection of its first reactor, quickly followed by the connection of other 3 reactors in 1975, 1980, and 1982, respectively. Subsequently, another 2 reactors began commercial operation in 1987 and 1991. However, during the accession negotiations of Bulgaria into the European Union, Bulgaria accepted the requirement of closing the first 4 reactors of the Kozloduy plant, since they were classified as not updatable to the European standards. In 1987, construction began on a new Belene nuclear plant, but the project was stopped in 1991 for lack of funds.

Fig. 3 shows wide fluctuations in the annual nuclear energy production. The proposed GMB identifies three negative shocks (Eq. (6)), one rectangular and two exponentials, that seem to catch the decreasing phases of the fluctuations. The first rectangular shock is of a modest effect between 1990 and 1995, and it represents a contraction phase since in this period only 1 reactor began commercial operation in 1991, while in the previous decade 3 reactors were connected to the grid (in 1980, 1982, and 1987). The two exponential shocks were detected around 1995 and 2000, both of a low effect that was not absorbed in time. Indeed, the last part of the Bulgaria's nuclear history is characterized by the closure of 4 reactors and the interruption of the construction of the Belene plant, as mentioned above. The forecasted reversion is fully believable, for the recent observed trend in reduction of energy production and for the lack of significant projects for the future.

3.5. The Slovak Republic

The Slovak Republic has 2 nuclear plants (Bohunice and Mochovce plants), for a total of 4 operational, 3 shut-down, and 2 under-construction reactors. The Bohunice plant started its commercial operation in 1972, connecting 3 reactors to the grid before 1980. The first reactor was closed in 1977 for a technical crash, and the other two were closed in 2006 and in 2008, respectively, classified as not updatable to European standards. At present, the Bohunice plant has two operational reactors, connected to the grid in August 1984 and in August 1985, respectively. The Mochovce plant started its commercial operation with 2 reactors connected to the grid in July 1998 and in December 1999. At present, another 2 reactors are under construction.

The proposed GMB includes one rectangular and one exponential shock (Eq. (6) without the second exponential shock). The rectangular shock is positive and is detected between 1984/85 ($1980 + a_3$) and 1998/99 ($1980 + b_3$). It corresponds to the commercial operation of 2 reactors at the Bohunice plant in 1984 and 1985. The exponential shock was found to be positive ($c_1 = 1.7365$), arising around 1999/2000 ($1980 + a_1$), and its effect is not yet absorbed in time

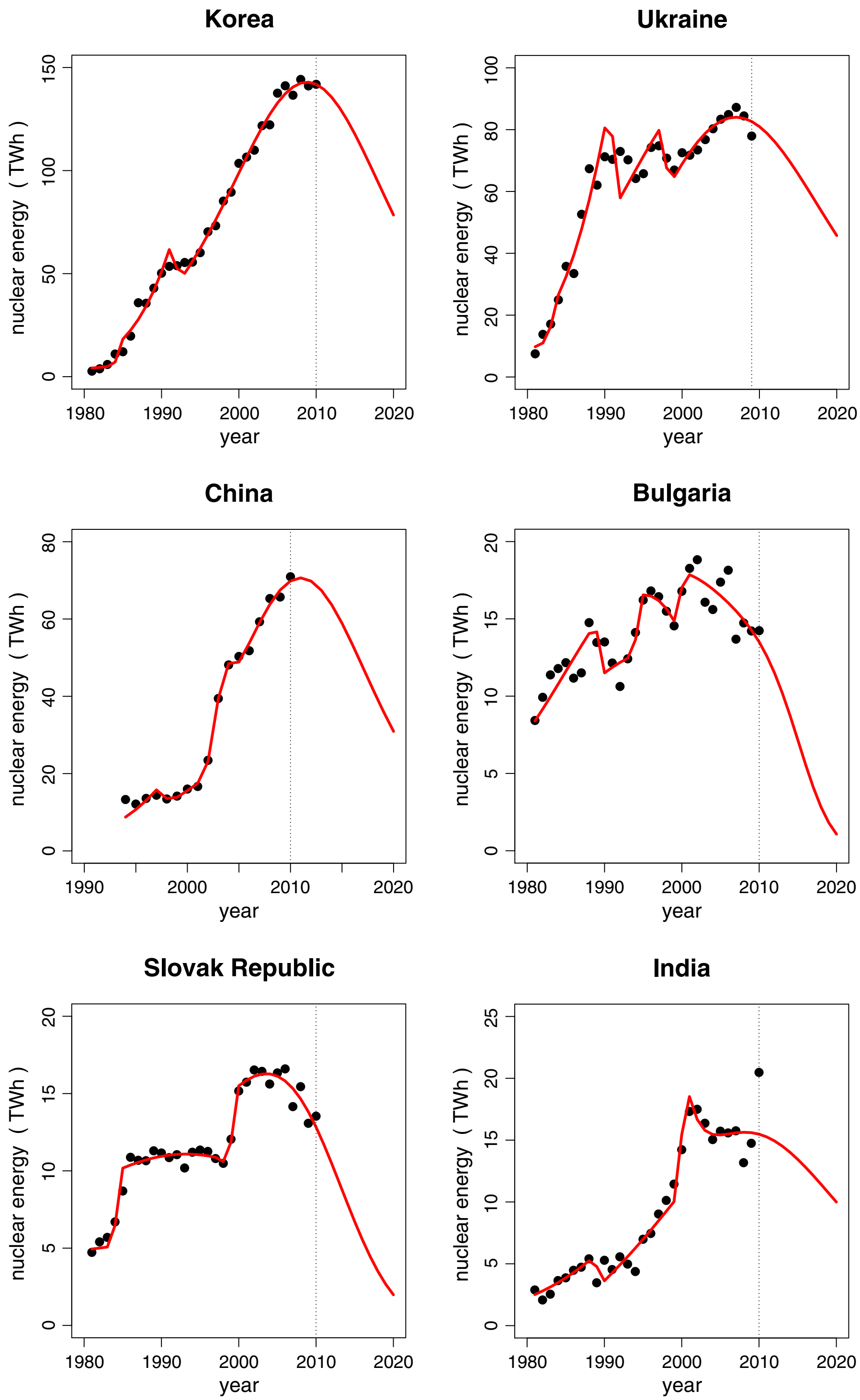

Fig. 3. Annual nuclear energy (TWh) and forecasts up to 2020. Fitted models correspond to GBMs of Table 1.

(b_1 is positive). This positive effect is due to the commercial operation of the 2 reactors at the Mochovce plant. The predicted trend of the proposed GBM, which depicts a declining production of nuclear energy, is confirmed by an observed contraction in the last 8 years due to the stoppage of 2 reactors at the Bohunice plant in 2006 and 2008. However, 2 reactors at the Mochovce plant are projected to begin commercial operation.

3.6. India

At the moment, India has 8 nuclear plants with 20 operational reactors and 5 reactors under construction (the same number as South Korea). The Tarapur plant began commercial operation in April 1969, the Rajasthan plant in November 1972, the Madras plant in July 1983, the Narora plant in December 1989, the Kakrapar plant in November 1992, the Kaiga plant in December 1999, the Kudankulam in February 2011, and the PFBR plant is under construction. India has quite a number of nuclear plants and reactors, but of small power, since India has no unified national grid and consequently has limited grid capacity.

The proposed GMB for India includes 2 exponential shocks (Eq. (6) without the rectangular shock). The first had a negative and absorbed impact around 1990, while the second had a positive and absorbed impact around 2000/2001. The first shock can be explained by a short time period in which no reactors were connected to the grid: from 1969 to 1989, 7 reactors were connected and, just after, 3 reactors were connected from 1992 to 1995. The second shock is explained by the commercial operation of 4 reactors from 1999 to 2000.

The model definitely underestimates the nuclear energy produced in the future, since it does not combine the behavior of the recent observations with the input from final three data. This does not allow the identification of a stable regime. The point is that from 2001 to 2004 no new reactors were connected to the grid, and a reactor planned for connection in 2007 was stopped due to the scarcity of available uranium in the country. The corresponding stationarity is easily shown in Fig. 3. As a consequence, in 2008 the country's nuclear energy production decreased, but then it steeply increased from 2009 to 2010. The reason for this particular behavior in recent years lies in the scarcity of the Russian uranium supply to India during 2004–2006, that was overcome in 2008 with the signing of a new agreement. This provided India with new opportunities for nuclear energy production and allowed connecting the reactor mentioned above.

India's dependency on Russia for its uranium supply is very strong, and the functioning of the 5 under-construction reactors of this country represents a great challenge in the future.

4. Uranium analysis

About 20 countries produce uranium. In 2008, Australia, Canada, Namibia, and Kazakhstan accounted for 70% of the world production, and just eight countries, Canada (21%), Kazakhstan (20%), Australia (19%), Namibia (10%), the Russian Federation (8%), Niger (7%), Uzbekistan (5%), and the United States (3%), accounted for about 93% of world production. The production in Kazakhstan has grown rapidly since 2006, and, in a very short time, it became the world's second-largest producer. Overall, world uranium production increased 4.1% from 2006 to 2007, 6% from 2007 to 2008, and 13% from 2008 to 2009. In 2009, uranium production reached 49 610 tU [9]. On the other hand, world uranium requirements amounted to 61 805 tU in 2009, with an increase of 4.6% from 2008. The significant question is: will the production of uranium meet long-term uranium requirements?

In the next section, we first outline a quantitative estimate, based on GBM, of the total extractable uranium, that will be compared with the geological estimates proposed by OECD [9]. Then, we propose, for both GBM and OECD estimates, possible scenarios for depletion time, according to uranium requirements expected by 2035. Finally, we propose a discussion about the feasibility of nuclear projects in the developing countries examined in Section 3.

4.1. Quantitative estimates of uranium availability, via GBM

As for the details of modeling the uranium time series, the proposed GMB identifies three negative shocks (Eq. (6)), one rectangular and two exponentials. For the results, see Table 1 and Fig. 4. The first shock is detected to be rectangular and of a positive effect from 1952/53 to around 1963 and can be explained by the arms race in those years. The second shock is detected to arise in 1978/79, and it is positive and completely absorbed in time. This shock is the consequence of nuclear plant development in the 1970,s and 1980's. The third shock is still positive; it arises around 1991, and it is positive and completely absorbed in time.

Total extractable uranium is estimated by GBM to be 3 347 710 tU (it corresponds to parameter m in Table 1 and is reported in Table 2). On the other hand, the OECD [9] estimates, based on geological certainty and production costs are IDR as 6 306 300 tU, and RAR as 4 004 500 tU (Table 2).

Since requirements of uranium amount to 2 464 185 tU in 2009, this means that, according to the GBM, only 26% of the total uranium is still usable (883 525 tU). However, according with the RAR and IDR (6 306 300 tU and 4 004 500 tU, respectively) and with the resulting availability, the percentage grows to 39% and 61%, respectively (Table 2). The GBM estimates are much more according to RAR, than to IDR. The GBM underestimates the total extractable uranium, since it does not catch the increasing trend of the last decade and especially of the last years. The growth is mainly due to mines recently opened in Kazakhstan, however it is known that the extractive capacity of those mines is limited [39].

4.2. Uranium depletion times by both GBM and OECD estimates

The depletion time of uranium, with the international actual nuclear policy, has been estimated, by the GBM, at around 2045, but the comments above suggest a more probable extended horizon.

However, which is the long-term perspective? It is well known that forecasts of installed capacity and uranium requirements point to future growth. Uranium demand is fundamentally driven by the number of operating nuclear reactors, which ultimately is driven by the demand of electricity. The International Energy Agency (IEA) states that 4800 GW of new generating capacity will be needed by 2030 to meet projected electricity demand. Indeed, an increase of 2.5% a year is expected, of which 80% will be required in non-OECD countries, such as India and China. World reactor uranium requirements by the year 2035 are projected to increase from 40% to 120%, with respect to 2009, while in the East Asia region, the growth is estimated from 120% to 180% [9]. With respect to predicted world growth, let us consider the lower (+40%) and the upper case (+120%). If we consider the uranium

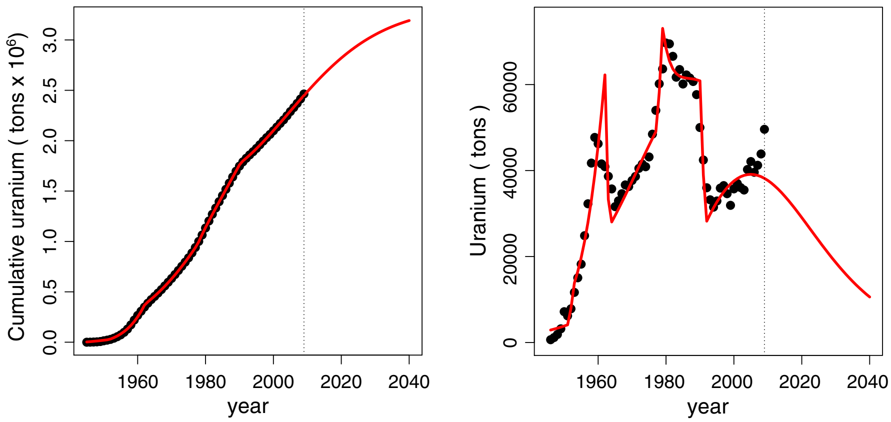

Fig. 4. Cumulative annual (left panel) and annual (right panel) uranium world extraction (tons) and forecasts up to 2040 (Table 1).

requirement of 61 805 tU in 2009, the predicted uranium requirement in 2035 would then be between 86 527 tU and 135 971 tU (+40% and +120%, respectively, in Table 3). Hypothesizing, for simplicity, a linear growth between 2009 and 2035, in the lower case, the available uranium will last until 2021 in the case of GBM, until 2025 in the case of RAR, until 2054 in the case of IDR. In the upper case, the depletion time will move to 2019 in the case of GBM, to 2029 in the case of RAR, and to 2042 in the case of IDR (Table 3). Again, the above comments about the effect of the Kazakhstan mines on depletion time furnished by GBM, suggest that here also the depletion time estimated by GBM should have a more probable extended horizon. The GBM information is more similar to the information given by RAR than that given by IDR.

4.3. Feasibility of nuclear projects for developing countries

Now we face the question of uranium availability from the perspective of meeting the needs of the nuclear projects of the developing countries in Section 3. Based on IAEA reactor data, it is known that of the currently 442 operational reactors, supposing a mean lifetime of 50 years, 196 will be still working in 2035. Of these 196 reactors, 63 will be in those developing countries (32%) considered in Section 3. Moreover, of the 65 reactors under construction, 45 will be in the developing countries (69%) considered in this paper. So, in 2035, hypothesizing that the nuclear projects will be fully realized, 108 reactors will be operational in the developing countries considered here, while 153 in the rest of the world (see Table 4). Considering the uranium requirements of 2035 provided for each single country by OECD [9], the proposed developing countries, that will have 41% of the operational reactors in the world, will require between 514 525 tU and 679 931 tU. This means that the above developing countries will require between 58% and 77% of the available uranium, according to GBM estimates, between 33% and 44% according to RAR, and between 13% and 18% according to IDR (see Table 2). As mentioned above for the depletion time, the percentages of the GBM should probably be intended as lower.

Since the nuclear projects in developing countries of Section 3, represent 41% (Table 4) of the nuclear projects in the world, given the uranium requirements presented above, it is apparent that such projected expansion is not fully credible. The only case in which these projects are practicable is, with the current technology of reactors, with the estimate of total extractable uranium by the IDR. However, the Inferred Resources are not defined with such a high degree of confidence [9].

The Fukushima disaster of 2011 reopened the debate about the use of nuclear energy to produce electricity. Since developed countries in years involved in nuclear energy did not choose to stop any operational reactors, little hope remains of fully meeting the desired nuclear projects in developing countries, given the current uranium demand and technology. Indeed, technological advancements may extend the use of the nuclear energy in the long-term. Advancements in reactor and fuel cycle technology aim not only at addressing economic, safety, and waste concerns, but also at increasing the efficiency with which

Table 2
Estimate of total extractable uranium given by the GBM, and by OECD [9] through RAR and IDR. Given the cumulative requirements of uranium up to 2009, available uranium is deduced in the three cases.

Requirements in 2009 (tU)		61 805
Cumulative requirements up to 2009 (tU)		2 464 185
Predicted total extractable (tU)	GBM	3 347 710
	OECD RAR	4 004 500
	OECD IDR	6 306 300
Availability in 2009 (tU)	GBM	883 525
	OECD RAR	1 540 315
	OECD IDR	3 842 115

Table 3
Uranium depletion time, using GBM uranium estimates, and RAR and IDR given by OECD [9]. Lower (+40%) and upper case (+120%) of uranium requirements in 2035, assessed by OECD [9], are considered.

	Lower case	Upper case
Requirements in 2035 (tU)	86 527	135 971
Corresponding annual linear growth (tU)	951	2853
GBM depletion time (year)	2021	2019
OECD RAR depletion time (year)	2025	2029
OECD IDR depletion time (year)	2054	2042

Table 4
Forecasts of operational reactors in 2035 both in the developing countries (of Section 3) and in the rest of the world, hypothesizing a mean lifetime of 50 years for current operational rectors and a full realization of reactors under construction.

Number of reactors	Developing countries	Rest of the world	Tot.
Now operational	63	133	196
Now under construction	45	20	65
Tot. operational in 2035	108	153	261

uranium resources are utilized. Indeed, the use of advanced reactors would also permit the use of other materials, such as uranium-238 and thorium, expanding the available resource base [9]. Expectations are focused on the realization of fast neutron reactors that could produce more fuel than they consume, since spent fuel could be recovered and reused (*Generation IV reactors*). However, this type of reactor remains far from implementation since, being optimistic for solving the design problems as scheduled, they are not expected to be available for commercial operation before 2040 [39]. The original timeline of 2030 is not more credible. One cause of the delay, as happened with Generation III reactors, is that safety risks may be greater initially since the workforce has little experience with the new designs.

5. Conclusions

Developing and graduated developing countries have little other chances beyond nuclear energy to confront their increasing energy demands. This paper models the time series of annual nuclear energy (TWh) of South Korea, Ukraine, China, Bulgaria, the Slovak Republic, and India using a diffusion framework. Their nuclear history in general is quite recent, and for some countries the estimated stage of the diffusion nuclear energy should be interpreted with caution since the last few data do not allow us to distinguish between reversion or stationarity. This is the case of South Korea, China, and India, while Ukraine, Bulgaria, and the Slovak Republic have already passed the middle of their life cycle. Some of these countries have very challenging nuclear projects for the near future, especially China, but also South Korea and India. Overall, the projected operational reactors in 2035 of developing countries will cover 41% of the total operational reactors in the world. The feasibility of the projects strictly depends on the availability of uranium. The GBM applied to the time series of the annual extraction of uranium provides less optimistic estimates of uranium availability and depletion time than those provided by OECD [9]. Following the GBM estimates, with the actual energy policy the supply of uranium will be sufficient until 2045. Note that horizons furnished by GBMs should probably be extended because of the recent growth of extractions, that will be limited, in the Kazakhstan mines.

For the near future, OECD [9] predicted a growth in 2035 of uranium requirements, between 40% and 120%; hypothesizing a linear growth for simplicity, the depletion time, considering the GBM estimates, decreases to 2021 and to 2019, respectively, considering the RAR to 2029 and 2025, respectively, and considering the IDR to 2054 and 2042, respectively. The nuclear projects of the developing countries appear challenging and not completely realistic, using both GBM and RAR estimates. The only case in which these projects are fully practicable is, with the current technology of reactors, if the estimate of the total extractable uranium is represented correctly by the IDR. Note that, the Inferred Resources are not defined with such a high degree of confidence. Improvements in reactor technology could help in the near future, since generation IV reactors are designed to produce more fuel than they consume. However, these technologies are still far from realization and the trial and error phase could be more complicated than scheduled to preserve the environment and worker safety in nuclear experiments.

References

[1] L. Mez, Nuclear energy-Any solution for sustainability and climate protection? Energy Policy 48 (2012) 56–63.
[2] WNA, World Nuclear Association, www.world-nuclear.org2012, (last accessed October 1, 2012).
[3] N. Lior, Energy resources and use: the present situation and possible paths to the future, Energy 33 (2008) 842–857.
[4] S. Choi, E. Jun, I. Hwang, A. Starz, T. Mazour, S. Chang, A.R. Burkart, Fourteen lessons learned from the successful nuclear power program of the Republic of Korea, Energy Policy 37 (2009) 5494–5508.
[5] S. Mallah, Nuclear energy option for energy security and sustainable development in India, Ann. Nucl. Energy 38 (2011) 331–336.
[6] J. Chow, R.J. Kopp, P.R. Portney, Energy resources and global development, Science 302 (2003) 1528–1531.
[7] http://www.ecosensorium.org/2010/11/china-tops-world-in-clean-energy.html, (last accessed October 1, 2012).
[8] Y.E. Lee, Y.B. Jung, Challenges of nuclear power for sustainable role in Korean energy policy, Energy Convers. Manage. 49 (2008) 1951–1959.
[9] OECD, Organisation for Economic Co-operation and Development Uranium 2009: Resources, Production and Demand, OECD Publishing, 2010.
[10] M. Guidolin, R. Guseo, A nuclear power renaissance? Technol. Forecast. Soc. Chang. (2012), http://dx.doi.org/10.1016/j.techfore.2012.05.014.
[11] L.A. Fourt, J.W. Woodlock, Early prediction of early success of new grocery products, J. Mark. 25 (1960) 31–38.
[12] E.M. Rogers, Diffusion of Innovations, The Free Press, New York, 1962.
[13] R. Guseo, A. Dalla Valle, M. Guidolin, World oil depletion models: price effects compared with strategic or technological interventions, Technol. Forecast. Soc. Chang. 74 (2007) 452–469.
[14] F.M. Bass, A new product growth model for consumer durables, Manag. Sci. 15 (1969) 215–227.
[15] T.C. Teng, V. Grover, W. Guttler, Information technology innovations: general diffusion patterns and its relationships to innovation characteristics, IEEE Trans. Eng. Manag. 49 (2002) 13–27.
[16] M.J. Libertore, D. Bream, Adoption and implementation of digital-imaging technology in the banking and insurance industries, IEEE Trans. Eng. Manag. 44 (1997) 367–377.
[17] T.R. Malthus, An Essay on the Principle of Population, J. Johnson, in St. Paul's Church-yard, London, 1798.
[18] P.F. Verhulst, Notice sur la loi que la population poursuit dans son accroissement, Corresp. Math. Phys. 10 (1838) 113–121.
[19] A.K. Laird, Dynamics of tumor growth, Br. J. Cancer 18 (3) (1964) 490–502.
[20] N. Meade, T. Islam, Forecasting with growth curves: an empirical comparison, Int. J. Forecast. 11 (1995) 199–215.
[21] A. Dalla Valle, C. Furlan, Forecasting accuracy of wind power technology diffusion models across countries, Int. J. Forecast. 27 (2011) 592–601.
[22] F.M. Bass, D.C. Jain, T.V. Krishnan, Modelling the marketing-mix influence in new-product diffusion, in: V. Mahajan, et al., (Eds.), New-Product Diffusion Models, International Series in Quantitative Market, 2000, pp. 99–122.
[23] V. Mahajan, E. Muller, F.M. Bass, New product diffusion models in marketing: a review and directions for research, J. Mark. 54 (1990) 1–26.
[24] H. Takada, D. Jain, Cross-national analysis of diffusion of consumer durable goods in Pacific Rim countries, J. Mark. 55 (1991) 48–54.
[25] T. Islam, D.G. Fiebig, Modelling the development of supply-restricted telecommunications markets, J. Forecast. 20 (2001) 249–264.
[26] D. Talukdar, K. Sudhir, A. Ainslie, Investigating new product diffusion across products and countries, Mark. Sci. 21 (2002) 97–114.
[27] S. Sundqvist, L. Frank, K. Puumalainen, The effects of country characteristics, cultural similarity and adoption timing on the diffusion of wireless communications, J. Bus. Res. 58 (2005) 107–110.

[28] J.P. Hsiao, C. Jaw, T. Huan, Information diffusion and new product consumption: a bass model application to tourism facility management, J. Bus. Res. 62 (2009) 690–697.
[29] F.M. Bass, T.V. Krishnan, D.C. Jain, Why the Bass model fits without decision variables, Mark. Sci. 13 (1994) 203–273.
[30] V. Mahajan, E. Muller, Y. Wind, New-Product Diffusion Models: From Theory to Practice, in: V. Mahajan, et al., (Eds.), New-product diffusion models, International Series in Quantitative Market, 2000, pp. 3–24.
[31] S. Makridakis, M. Hibon, The M3-Competition: results, conclusions and implications, Int. J. Forecast. 16 (2000) 451–476.
[32] T. Islam, D.G. Fiebig, N. Meade, Modelling multinational telecommunications demand with limited data, Int. J. Forecast. 18 (2002) 605–624.
[33] B.G. Hardie, P.S. Fader, An empirical comparison of new product trial forecasting models, J. Forecast. 17 (1998) 209–229.
[34] V. Kumar, V. Krishnan, Multinational diffusion models: an alternative framework, Mark. Sci. 21 (2002) 318–330.
[35] R. Guseo, Strategic interventions and competitive aspects in innovation life cycle, Working Paper Series, N. 11, 2004.
[36] R. Guseo, A. Dalla Valle, Oil and gas depletion: diffusion models and forecasting under strategic intervention, Stat. Methods Appl. 14 (2005) 375–387.
[37] M. Guidolin, C. Mortarino, Cross-country diffusion of photovoltaic systems: modelling choices and forecasts for national adoption patterns, Technol. Forecast. Soc. Chang. 77 (2010) 279–296.
[38] G. Seber, C. Wild, Nonlinear Regression, Wiley, New York, 1989.
[39] M. Dittmar, The Future of Nuclear Energy: Facts and Fiction: An Update Using 2009/2010 Data, http://arxiv.org/pdf/1101.4189v1.pdf2011, (last accessed October 1, 2012).

Alessandra Dalla Valle is an Assistant Professor of Statistics at the School of Economics and Political Science of the University of Padua, Italy (Department of Statistical Sciences). Born in 1967 and educated in Statistics at the University of Padua, she had a Ph.D. in "Multi-variate skew normal distribution". Her research areas include skew normal theory and applications, competition modeling, wind power technology spread, and oil and gas depletion.

Claudia Furlan is an Assistant Professor of Statistics at the School of Economics and Political Science of the University of Padua, Italy (Department of Statistical Sciences). She graduated in Statistics in 2001 and she received her Ph.D. in Statistics in 2005. Her research areas include diffusion models, adoption processes, wind power technology spread, statistical modeling and Bayesian techniques.