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A nuclear power renaissance?

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Abstract: Nuclear energy has been experiencing a revival in many countries, since it is considered to be a possible substitute for fossil fuels for electricity generation. This calls for a focused analysis, in order to evaluate whether conditions exist for its wide employment. While typical aspects against this option have to do with waste management, security of power plants and related health concerns, other issues less frequently considered by politics, mass media, and public opinion seem particularly crucial to understand if we are really going to face a nuclear energy renaissance. In particular, nuclear energy is well known to depend on parallel dynamics of uranium extraction and reactor startup. In this paper we apply an innovation diffusion framework to model co-evolutionary processes of uranium extraction, reactor startup and nuclear energy consumption at a world level. We also perform an analysis of nuclear consumption dynamics in France, Japan, and the USA, which are the three countries that are mostly invested in it. The results obtained by analyzing all of these processes do not seem to support the idea of a new era for nuclear energy.

Keywords: Innovation diffusion models, Uranium extraction, Nuclear power consumption, Reactors.

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Abstract: Nuclear energy has been experiencing a revival in many countries, since it is considered to be a possible substitute for fossil fuels for electricity generation. This calls for a focused analysis, in order to evaluate whether conditions exist for its wide employment. While typical aspects against this option have to do with waste management, security of power plants and related health concerns, other issues less frequently considered by politics, mass media, and public opinion seem particularly crucial to understand if we are really going to face a nuclear energy renaissance. In particular, nuclear energy is well known to depend on parallel dynamics of uranium extraction and reactor startup. In this paper we apply an innovation diffusion framework to model co-evolutionary processes of uranium extraction, reactor startup and nuclear energy consumption at a world level. We also perform an analysis of nuclear consumption dynamics in France, Japan, and the USA, which are the three countries that are mostly invested in it. The results obtained by analyzing all of these processes do not seem to support the idea of a new era for nuclear energy.

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1 Introduction

Economic and social systems depend on energy availability. In the past, complex societies collapsed when unable to combine energy needs with the limited availability of resources on earth. Today we are seeing a growing competition among countries for natural resources and energy provision, because forecasts regarding the depletion of fossil fuels, which still represent the most important energy source employed for human activities, are definitely showing the very finite nature of earth. Climate change represents another problem calling for a prompt and adequate answer by national governments.Thus, the energy issue has reached the top of many political agendas.

A number of available options are available to face energy related problems:

the renewable energy option, which is based on a large scale exploitation of solar, wind, geothermal and biomass sources; the nuclear energy option, which, unlike renewables, would guarantee a non-intermittent source of electricity; and the energy reduction option, which, would require an improvement in technologies efficiency and a substantial change in people's life style (especially in developed countries).

Perhaps not surprisingly, we have witnessed a growing interest among nations in nuclear energy. Indeed, nuclear energy represents a powerful alternative for providing uninterrupted electricity, and for facing the global warming problem, since it does not produce any direct CO_2 emission. Perhaps for some of its attracting properties, some countries are envisaging a return to it, and building or planning to build new reactors (even Italy, which refused nuclear power in 1987 with a popular referendum). This technology has obviously stimulated the public debate in order to show benefits on the one hand and drawbacks on the other; in particular, much of this debate is concentrated on waste management and security aspects, which seem to hold the balance of power for a decision in favour or against the nuclear option.

The security aspects fairly play a central role in discussion; however, there are other elements, less considered by politics, mass–media and public opinion, representing crucial variables for a possible new nuclear era: as stressed by the Energy Watch Group [7], any analysis of the development of nuclear power in the next 25 years should concentrate on the supply of uranium and the addition of new reactor capacity.

Actually, one of the points typically used by nuclear power advocates is security in energy provision: the nuclear option would remove all of the uncertainties connected with oil and natural gas supply. However, uranium itself is a scarce resource, available in few and sometimes insecure countries.
Since 1945 about 2.3 million tons of uranium have already been produced at world level. It is generally reported that in the early years before 1980, uranium production was strongly driven by military uses. The breakdown of the Soviet Union, with the end of the cold war, led to the conversion of nuclear material into fuel for civil uses and was (at least partially) responsible for the production decline that occurred at the end of 1980s. Today, the ten largest uranium consumers are the USA, France, Japan, Russia, Germany, SouthKorea, United Kingdom, Ukraine, Canada and Sweden, but only four of these countries, namely Canada, Russia, USA and Ukraine are still extracting uranium in sizable quantities. Germany and France have stopped uranium mining, while Japan, United Kingdom, SouthKorea and Sweden never had substantial uranium mining on their territory [5]. The latest report of the Euratom Supply Agency registers that only 2.73% of the uranium employed in European power stations came from Europe. The rest mainly came from Kazakhstan, Uzbekhstan, and Niger.

As far as reactors are concerned, most were built between 1965 and 1975, while the peak of grid connections was reached in 1984. About 85% of the existing reactors worldwide have been operating for more than 15 years. In 2009, there were 435 nuclear reactors operating in the world, nine less than in 2002, and for the first time since commercial use of nuclear energy in the middle of the 1950s, no new nuclear plant was connected to the grid in 2008.

The World Nuclear Industry Status Report 2009 [13] claims that for practically all of the potential newcomers it remains unlikely that fission power programs can be soon implemented within the required technical, political, and economic framework. In particular, the lack of trained workforce and loss of competence are among the most difficult challenges to overcome. Even France, the country with the strongest base of civilian nuclear competence, is suffering from shortage of skilled labour: the two Generation III reactors, managed by the French AREVA, currently under construction in Finland (Olkiluoto) and France (Flamanville), have experienced cost explosions, delays, and many design problems (see [13] and [6]). Moreover, in 2009 the number of produced electric energy from nuclear fission was 1.6% smaller than in 2008.

Following the suggestion of the Energy Watch Group in [7], the purpose of this paper is to provide an analysis of the nuclear sector by first considering the dynamics of uranium extraction and reactor startups. As a second step, we propose an analysis of electricity demand from nuclear at world level, and in the three countries that together hold more than 60% of operational reactors, namely USA, France, and Japan. We wish to describe and forecast the evolution of these processes, in order to provide a contribution to the debate on whether there are the conditions for a return to nuclear energy. We develop our analysis by using innovation diffusion models, whose typical purpose is to describe and forecast the process of adoption of an innovation into a market or social system. The physicist Marchetti in [12] was one of the first to employ the innovation diffusion framework to analyze energy dynamics by using a logistic model. He hypothesized that new energy sources, when launched into markets, may be considered as standard commercial products, which may be accepted or not by persons, who express their approval through a process of social learning. This one–cycle learning process is well represented by logistic models, and more generally by the Bass models, BM and GBM, (see [1], [2]) which can describe and forecast the adoption of an innovation by accounting both for the effects of internal adoption dynamics, due to consumers' behaviour, either innovative or imitative, and for external perturbations, like policy measures and environmental upheavals, which may influence the speed of the process. Specifically, the Generalized Bass model, GBM, was profitably employed to analyze the adoption of energy sources, like oil, photovoltaic, and wind energy ([9], [8], [4]).

In this paper we will use the same class of models to describe the dynamics of uranium extraction, reactor startups and shutdowns, and nuclear power consumption; in fact, these may be interpreted as three different diffusion processes in which an innovation -uranium, reactors, nuclear energy- is adopted on the basis of final affordable decisions.

The paper is structured as follows. In Section 2 we describe the class of diffusion models we will employ in our analyses. In Section 3, we carry out a joint analysis of uranium extraction and reactor startups and shutdowns dynamics, pointing out an interesting correlation among these processes. In Section 4, we study the diffusion of nuclear energy in the world and in France, by adopting two different evolutionary hypotheses: a Bass–like evolution, under which the diffusion of nuclear energy is characterized by a single, finite life–cycle, and a Norton-Bass–like evolution, which is based on an asymptotic stationary model, assuming an indefinite life–cycle. Section 5 is devoted to final comments and discussion. In Appendix A, we analyze the cases of nuclear power consumption in Japan and the USA, which confirm the results obtained for France.

2 Innovation diffusion models

The Generalized Bass model, GBM, [2], was introduced to generalize the structure of the Bass model, BM, [1], in order to take into account the effect of external control variables on the diffusion process. Originally conceived to identify typical marketing mix measures, it has shown its great flexibility in describing several kinds of perturbations occurring within a diffusion process. The model takes the form of a differential equation

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

whose closed-form solution, under initial condition $z(0) = 0$, is

$$z(t) = m\frac{1 - e^{-(p+q)\int_0^t x(\tau)d\tau}}{1 + \frac{q}{p}e^{-(p+q)\int_0^t x(\tau)d\tau}}, \qquad 0 \leq t < +\infty. \tag{2}$$

In Equation (1) the rate of adoptions, $z'(t)$, is proportional to the residual market, $(m - z(t))$, where m is the *market potential* (or *carrying capacity*), i.e. the maximum number of realizable adoptions, and $z(t)$ is the cumulative number of adoptions at time t. The residual market is modulated by parameters p and q, where p represents adoptions of *innovators*, and q is the so called *coefficient of imitation,* whose influence is modulated by the ratio $z(t)/m$.

The effect of external interventions or shocks is described through function $x(t)$, which acts on the natural shape of diffusion, and modifies the adoption process by expanding the residual market, $(m - z(t))$, for $x(t) > 1$, or reducing it, for $x(t) < 1$. The Bass model, BM, is a particular case of the GBM when $x(t) = 1$.
Function $x(t)$ may take different forms if we want to describe rare shocks; a strong and fast perturbation may be represented with exponential function components, namely $x(t) = 1 + c_1 e^{b_1(t-a_1)} I_{t \geq a_1} + c_2 e^{b_2(t-a_2)} I_{t \geq a_2}$, where parameters c_1 and c_2 represent the depth and sign of interventions, b_1 and b_2 describe the persistency of the induced effects and are negative if the memory of these interventions is decaying to the stationary position (mean reverting), and a_1 and a_2 are the starting times of interventions. A more stable perturbation acting on diffusion for a relatively long period, like institutional measures and policies, may be described by a rectangular function $x(t) = 1 + cI_{t \geq a} I_{t \leq b}$, where parameter c describes the perturbation intensity and may be either positive or negative, while parameters a and b define the temporal interval in which the shock occurs. Function $x(t)$ may also include covariates acting as input variables.

A generalization of the Bass models was proposed by Guseo and Guidolin in [10], by relaxing the assumption of a constant market potential, and describing the market potential as function of a latent communication process which develops over time. The model proposed in [10] is based on a special Cellular Automata (CA) description whose aggregate mean–field approximation, in continuous time, yields

$$z'(t) = m(t)\left\{-r_s\frac{z(t)}{m(t)} + \left(p_s + q_s\frac{z(t)}{m(t)}\right)\left(1 - \frac{z(t)}{m(t)}\right)\right\}x(t) + z(t)\frac{m'(t)}{m(t)}, \qquad (3)$$

where $z'(t)$ represents instantaneous adoptions at time t, $z(t)$ denotes the corresponding cumulative adoptions, p_s and q_s are the usual Bass like parameters depicting innovation (external) and imitation (internal) effects, and r_s accounts for a possible decay effect due to not retained adoptions. Function $m(t)$ is the dynamic market potential, and function $x(t)$ represents the usual intervention tool (environmental or strategic perturbations).

The closed form solution of model (3), produced in [10]), is

$$z(t) = m(t)\frac{1 - e^{-D_s\int_0^t x(\tau)d\tau}}{\frac{1}{{}_sr_2} - \frac{1}{{}_sr_1}e^{-D_s\int_0^t x(\tau)d\tau}}, \quad D_s = \sqrt{(q_s - p_s - r_s)^2 + 4q_sp_s} > 0, \qquad (4)$$

where ${}_sr_i = (-(q_s - p_s - r_s) \pm D_s)/(-2q_s),\ i = 1, 2$, with ${}_sr_2 > {}_sr_1$. The second factor in equation (4) describes *adoption dynamics* under the modulation of the market potential factor, $m(t)$. In this model, particular attention is devoted to providing a general definition of the market potential through a non–negative function $m(t) \geq 0$, which may be modelled in different ways. In [10], the following structure is developed

$$m(t) = K\sqrt{\frac{1 - e^{-(p_c+q_c)t}}{1 + \frac{q_c}{p_c}e^{-(p_c+q_c)t}}}. \qquad (5)$$

where p_c and q_c respectively denote the external and internal components of the *communication process*, while K is the asymptotic market potential. The final model, in its reduced form (with $r_s = 0$ and $x(t) = 1$) is

$$y(t) = K\sqrt{\frac{1 - e^{-(p_c+q_c)t}}{1 + \frac{q_c}{p_c}e^{-(p_c+q_c)t}}}\ \frac{1 - e^{-(p_s+q_s)t}}{1 + \frac{q_s}{p_s}e^{-(p_s+q_s)t}}. \qquad (6)$$

Equation (6) clarifies that a diffusion process is composed of two co-evolutionary phases, communication, and adoption.

To estimate the models' parameters, a nonlinear least squares approach, NLS, (e.g. Levenberg-Marquardt) is adopted; in particular, we may consider the structure of a nonlinear regression model:

$$w(t) = f(\beta, t) + \varepsilon(t) = z(t) + \varepsilon(t), \qquad (7)$$

where $w(t)$ is the observed response, $f(\beta, t)$ is the deterministic component, depending on parameter β and time t, and $\varepsilon(t)$ is a i.i.d. residual term. A more refined approach is based on ARMA models with a standard non-parametric NLS estimation as a first step, in order to provide an adequate treatment to autocorrelated residuals, calculated as $w(t) - f(\hat{\beta}, t)$ (see, for instance, [10]).

3 Worldwide uranium extraction and reactor startups and shutdowns

In this section, we propose a joint analysis of the dynamics of uranium extraction, and reactor startups and shutdowns. If we look at the time series of uranium extraction and reactor startups (see Figure 1, data source: International Energy Agency, IEA; World Nuclear Association, WNA; International Atomic Energy Agency, IAEA) we may appreciate the correlation between the two. In fact, we will see that some perturbation occurring in one may be interpreted through the dynamics of the other. We begin our analysis by considering the supply dynamics of uranium, since its availability is the basic requirement for the production of nuclear energy.

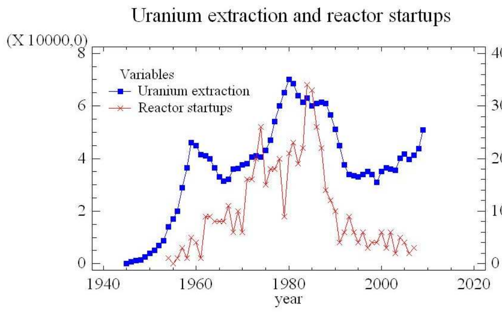


Figure 1: Dynamics of uranium extraction (in tons) and reactor startups

The description of uranium supply dynamics is a difficult task, because of uncertainties in data collection. Although the current classification of uranium resources by categories and cost classes gives the impression of high quality data, the reality seems to be quite different (see [7]). Usually, only Reasonably Assured Resources (RAR) below $40 - 80\$/Kg$ U are comparable with proved resources referring to crude oil. Reasonably assured resources between 80 and $130\$/Kg$ U and Inferred Resources (IR) are considered as possible resources, while the so-called Undiscovered Resources cannot be used in projections. Among various criteria adopted for determining whether uranium can be easily mined or not, the ore grade is the most relevant one; in fact, the energy requirement for uranium mining increases as the ore concentration decreases. In particular, uranium mining with ore content below 0.01% makes sense under special circumstances [7]. About 90% of worldwide resources have ore grade below 1%, and more than 2/3 below 0.1%. The resources with highest probability are in Australia, Canada and Kazakhstan, even if the only country with ore grade larger than 1% is Canada. Today one fourth of the uranium employed in world power stations comes from the “Megatons to Megawatts Program”, signed by United States and Russia in 1993 and recently renewed by Obama and Putin, on the grounds of nonproliferation commitments, in order to convert high-enriched uranium taken from dismantled Russian nuclear weapons into low-enriched-uranium for nuclear fuel. While the Euratom Supply Agency and the Nuclear Energy Agency provide optimistic projections on uranium availability, others have a more pessimistic view; for instance, the Energy Watch Group in [7] stated that the analysis of uranium resources leads to the assessment that discovered reserves are not sufficient to guarantee the resource supply for more than thirty years. The official worldwide uranium mining results for 2009 are 50772 tons, so that 2428653 tons have been extracted since 1945. The result reported in 2009 is based almost entirely on the contribution of Kazakhstan, which increased its annual production, from 8521 tons to 14020 tons. Uranium mines in Canada have again reached the 2006 levels of about 10000 tons. Despite the impressive increase in Kazakhstan, the reported uranium mining from all other countries has stagnated for several years at around 37000 tons [6]. According to the just published edition of the Red Book, the joint document from IAEA and NEA (Nuclear Energy Agency for OECD countries), which provides information on exploitable uranium resources, new large uranium mines with a production capacity of more than 2000 tons are supposed to start operations during the next 5 years in Kazakhstan, Namibia, Niger, Canada, and Jordan. The authors of the Red Book state that the world uranium mining capacity is expected to reach a maximum of 98000–141000 tons around the year 2020, followed by a decline to 80000–129000 tons in 2025, and 68000–109000 tons in 2035 (see [6]). However, their uranium mining capacity estimates prove very different from the much lower real production; for a quite detailed analysis of the questionable reliability of Red Book's data, [5] and [6].

Instead of trying to provide a direct estimate of uranium reserves, we propose an indirect modelling through the time series of uranium extraction (in tons), which goes from 1945 to 2009 (data source: IEA and WNA).

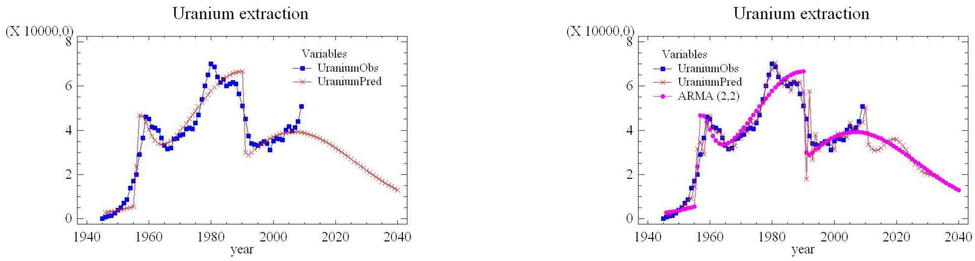
Table 1: Uranium extraction: parameter estimates for a GBM with two exponential shocks. ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.999841$ is a determination index based on cumulative data

m	p	q	c_1	b_1	a_1
3.43113E6	0.00073	0.07603	6.18712	-0.41179	11.53440
(3.05885E6)	(0.00052)	(0.07131)	(4.35170)	(-0.52243)	(10.87970)
(3.80342E6)	(0.00094)	(0.08074)	(8.02254)	(-0.30115)	(12.18920)
c_2	b_2	a_2	R^2		
-0.59842	-0.03728	46.06740	0.999841		
(-0.67291)	(-0.06416)	(45.41920)			
(-0.52393)	(-0.01040)	(46.71570)			

Our contribution may be placed within the debate on the so–called Peak Uranium, which is defined as the time at which the maximum global uranium production is reached. After the peak, the production declines until complete depletion. The concept of peak uranium follows from Hubbert's peak theory extensions, most commonly associated with the peak oil concept, and stresses the fact that uranium is a finite resource, with a limited production life–cycle. For this reason we feel that

Table 2: Uranium extraction: ARMA (2,2) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$AR(1)$	$AR(2)$	$MA(1)$	$MA(2)$	$Mean$
1.71340	-0.870148	0.508377	0.56992	57.71230
(22.41340)	(-11.41930)	(4.78858)	(4.60910)	(2.69958)
[0.00000]	[0.00000]	[0.00001]	[0.00002]	[0.00900]



(a) (b)

Figure 2: Dynamics of uranium extraction: (a) Generalized Bass model with two exponential shocks, (b) ARMA (2,2) sharpening on autocorrelated residuals

the use of innovation diffusion models is legitimate; when the extraction of uranium began, in 1945, it could be considered an innovation, whose diffusion depended on parallel diffusion processes of uranium–based technologies (both for military and civil purposes). Among the models fitting this time series, the most satisfactory, with a good determination index $R^2 = 0.999841$, is a GBM with two exponential shocks, presented in Table 1. The first shock which occurred in 1956 ($a_1 = 11.53$), was a very strong one ($c_1 = 6.18$), and may be interpreted as an acceleration to the process of extraction due to the connection to the grid of the first reactors, started in 1954. The model identifies a second shock in 1991 ($a_2 = 46.06$), with negative intensity ($c_2 = -0.59$) and negative memory ($b_2 = -0.037$). In this second case the interpretation of this perturbation may be related to the parallel process of reactor startups as well; a simple inspection of Figure 1 shows that this negative shock to uranium production occurred exactly after a decline in reactor connections to the grid at the end of the 80s, which may be partially justified by the effects of the Chernobyl accident. Although we may observe a restarting of extraction in recent years, as shown in Figure 2, which may be imputed to the increased mining in Kazakhstan, the model substantially forecasts a declining dynamic, which will lead to uranium exhaustion in about 30 years. In fact, the uranium boom in Kazakhstan is presented with a short lifetime [6]. The analysis of the residual component is efficiently completed with an ARMA (2,2), in order to treat properly autocorrelation effects. See in particular Table 2 and Figure 2.

The process of reactor startups, begun in 1954, is characterized by two waves of

Table 3: Reactor startups: parameter estimates for a GBM with a rectangular and an exponential shock. ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.999796$ is a determination index based on cumulative data

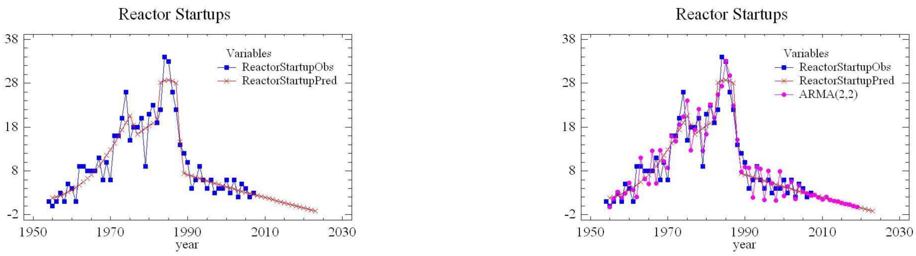
m	p	q	c_1	b_1	a_1
773.072	0.00189	0.14478	-0.71860	0.01091	34.35030
(696.976)	(0.00172)	(0.13525)	(-0.77096)	(0.00566)	(33.96090)
(849.169)	(0.00206)	(0.15431)	(-0.66624)	(0.01615)	(34.73970)
c_2	b_2	a_2	R^2		
-0.29843	22.45170	28.93090	0.999796		
(-0.35846)	(21.42110)	(27.90810)			
(-0.23841)	(23.48230)	(29.95380)			

Table 4: Reactor startups: ARMA (2,2) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$AR(1)$	$AR(2)$	$MA(1)$	$MA(2)$	$Mean$
-0.72564	-0.03776	-1.41905	-0.98851	-0.15985
(-5.22092)	(-2.51815)	(-38.60210)	(-21.37950)	(-0.29928)
[0.00000]	[0.01511]	[0.00000]	[0.00000]	[0.76598]

grid connection (see Figure 1). The first one had its peak in 1974 with 26 connections to the grid, while the second reached its maximum in 1984 with 34 (data source: IAEA PRIS). In between, we may see that the process passed through a long depression, followed by a fast resumption, and a strong slowdown observable at the end of the 1980s. The best model fitted to this time series is a GBM with a rectangular and an exponential shock, with a determination index $R^2 = 0.999796$ (see Table 3). The model well identifies the long depression by estimating a negative rectangular shock between 1975 ($b_1 = 22.45$) and 1983 ($a_1 = 28.93$); this may be interpreted as an effect of the 1970s' oil shocks, which had negative outcomes on all industrial activities. The second shock estimated by the model starts in 1987 ($a_2 = 34.35$), has negative intensity ($c_2 = -0.7186$), and may be reasonably explained as a slackening in grid connection after the effects of the Chernobyl accident. Interestingly, we may observe that the effects of this perturbation are persistent, as confirmed by the positive value of parameter $b_2 = 0.0109$. After this shock, the process of reactor startups has not experienced an inversion, and the trend for the next years is a consistent decline (see Figure 3). An ARMA (2,2) is applied to autocorrelated residuals with satisfactory results (see Table 4 and Figure 3(b)).

The proposed GBM, with two exponential shocks for the analysis of uranium extraction seems to underestimate the most recent production. The direct comparison with the reactor startups series in Figure 1 and the declining trend predicted by the GBM applied to it, highlights a divergence in behaviour between uranium and reactors, showing opposite monotonicities. This is just an apparent contradiction; it may be interpreted as the consequence of the process known as "uprating", that is the extension of operating licenses of several plants. For instance, in [13] it is



(a) (b)

Figure 3: Dynamics of reactor startups: (a) Generalized Bass model with a rectangular and an exponential shock, (b) ARMA (2,2) sharpening on autocorrelated residuals

reported that US plants had their operating licenses extended from 40 to 60 years. As of July 2009, 54 of the 104 US nuclear plants had been granted a life extension license by the Nuclear Regulatory Commission and other projects are being developed in order to allow other reactors to operate for up to 60 years. There is a wide perception that these technical alterations at existing plants will apply in other countries, which may justify the locally growing trend in uranium extraction observed in the most recent years.

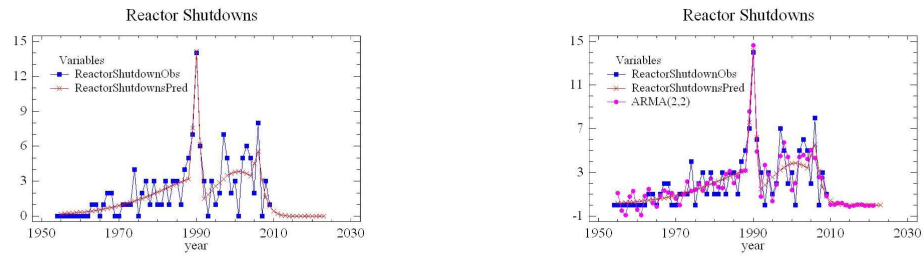
Table 5: Reactor shutdowns: parameter estimates for a GBM with an exponential and a rectangular shock. ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.998971$ is a determination index based on cumulative data

m	p	q	c_1	b_1	a_1
128.648	0.00130	0.10721	2.94829	0.03311	35.57090
(126.009)	(0.00107)	(0.09882)	(1.65404)	(0.02011)	(35.08540)
(131.287)	(0.00154)	(0.11559)	(4.24253)	(0.04610)	(36.05640)
c_2	b_2	a_2	R^2		
-3.816470	37.37800	51.70120	0.998971		
(-5.16373)	(37.009600)	(50.65540)			
(-2.46921)	(37.746300)	(52.74710)			

Such interpretation of results may be confirmed through the analysis of the reactor shutdowns series, produced in Table 5, Table 6, and Figure 4. As we may see, shutdowns have been slower than startups, and the best model fitting this series is a GBM with an exponential and a rectangular shock, $R^2 = 0.998971$, efficiently completed with an ARMA (2,2). In particular, the first shock, occurring in 1989 ($a_1 = 35.57$), was quite intense ($c_1 = 2.94$), and led to a peak in shutdowns in 1990, probably due to the effects of the Chernobyl accident, which had negative consequences on startups and accelerated shutdowns. The second shock, a negative one

Table 6: Reactor shutdowns: ARMA (2,2) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$AR(1)$	$AR(2)$	$MA(1)$	$MA(2)$	$Mean$
0.43727	-0.66532	0.03989	-1.02693	-0.33793
(3.83160)	(-5.82339)	(1.91489)	(-50.08460)	(-1.45595)
[0.00035]	[0.01511]	[0.06112]	[0.00000]	[0.15153]



(a) (b)

Figure 4: Dynamics of reactor shutdowns: (a) Generalized Bass model with a rectangular and an exponential shock, (b) ARMA (2,2) sharpening on autocorrelated residuals

($c_2 = -3.81$), has been identified between 1991 ($b_2 = 37.37$) and 2005 ($a_2 = 51.7$), and indicates a strong slackening in shutdowns not followed by a resumption. In fact, the model forecasts a substantially declining trend for this series. At first sight, this may appear a strange result, because one would expect that shutdowns would continue in the future; however, this is coherent with the interpretation given to the divergence between uranium extraction and reactor startups; no startups or shutdowns, just an extended life–cycle of existing plants.

4 Nuclear power consumption

We dedicate this section to the analysis of nuclear power consumption in the world and in France, one of the countries most invested in it. We also develop an analysis of the cases of Japan and the USA, which is presented in Appedix A, in order to avoid repetitions here. The data source is the BP Statistical Review of World Energy 2010 [3], which provides the series of nuclear energy consumption from 1965 to 2009 in TeraWatt–hours (TWh). For each of the cases examined, we adopt two different viewpoints: the first one assumes that consumption dynamics may be described as a process with a single, limited life–cycle, characterized by typical phases of take–off, growth, maturity, and decline, while the second one takes a Norton–Bass interpretation of diffusion, which assumes that, after a growth phase, the process

Table 7: World: parameter estimates for a model with a dynamic potential (Guseo and Guidolin, 2009). ( ) marginal linearized asymptotic 95% confidence limits

K	p_c	q_c	p_s	q_s	R^2
140976	0.00149	0.22461	0.00233	0.07374	0.999986
(128847)	(0.00132)	(0.21743)	(0.00227)	(0.06857)	
(153106)	(0.00166)	(0.23179)	(0.00238)	(0.07892)	

Table 8: World: ARMA (2,1) on autocorrelated residuals; ( ) t-statistic, [ ] p value

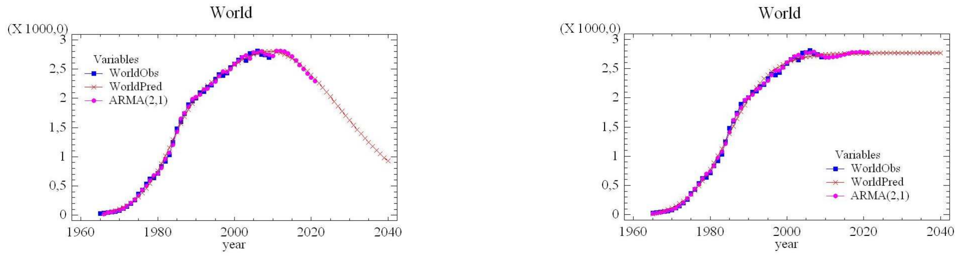
$AR(1)$	$AR(2)$	$MA(1)$	$Mean$
1.72002	-0.95588	0.93570	-0.90652
(31.38440)	(-17.33190)	(9.07148)	(-0.34627)
[0.00000]	[0.00000]	[0.00000]	[0.73091]

reaches an asymptotic stationary level for an indefinite time. The Norton–Bass view of diffusion, based on instantaneous data of adoption, is suitable for situations with successive generations of technology; in this context, we will use it as an alternative to the life–cycle view, whose forecasts may appear somehow restrictive.

The commercial use of nuclear fission begun around 50 years ago. In 2010, 441 were operating power plants in 30 countries, but the majority operate in Western Europe, North–America, Japan, and South Korea. The data series of world nuclear consumption show that the process has experienced a quite evident slackening in recent years. In particular, the number of produced TWh in 2009 (2560 TWh) was the lowest since at least 2005. This fact may be interpreted in conformity with the model selected. Adopting the finite life–cycle view, we found that the most suitable structure for this series is one with a dynamic potential, as proposed in [10], with a very good level of fitting, $R^2 = 0.999986$ (see Table 7) and completed with an ARMA (2,1) on autocorrelated residuals (see Table 8 and Figure 5(a)). In particular, we see that the model perfectly captures the acceleration to the process occurred in the early 1980s, followed by a slowdown begun ten years later. The ability to recognize this particular behaviour by the model with dynamic potential has been highlighted

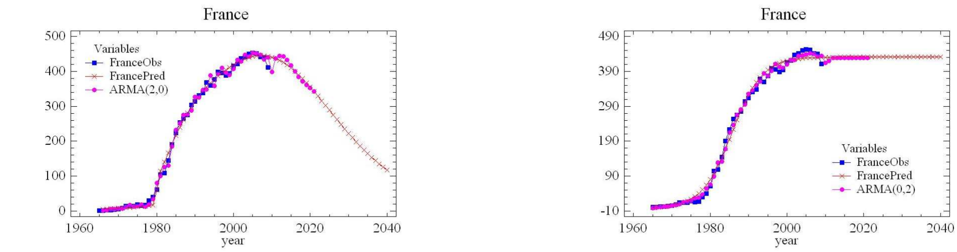
Table 9: World: parameter estimates for a BM on instantaneous data (Norton–Bass). ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.996641$ is a determination index based on instantaneous data

m	p	q	R^2
2765	0.00400	0.17907	0.996641
(2713)	(0.00329)	(0.16587)	
(2816)	(0.00472)	(0.19226)	



(a) (b)

Figure 5: World nuclear power consumption: Guseo and Guidolin (2009) model and ARMA (2,1) in a life–cycle perspective (a), BM and ARMA (2,1) in a Norton–Bass perspective



(a) (b)

Figure 6: Nuclear power consumption in France: GBM with one exponential shock and ARMA (2,0) in a life–cycle perspective (a), BM and ARMA (0,2) in a Norton–Bass perspective

in [11], grounding the presence of a slowdown with the interaction between the two phases of a diffusion process, namely communication and adoption. In the case of nuclear consumption, the communication phase may be interpreted as the diffusion of technical knowledge on nuclear energy, which represents the basic requirement for its subsequent adoption. Indeed, we may clearly notice that consumption accelerated right after the oil shocks of the 1970s, and in parallel with an acceleration in uranium extraction and reactor connection to the grid, occurring in the early 1980s. Likewise, the negative shocks to uranium production and reactor startups may be related to the slowdown to consumption of the early 1990s. Figure 5(a) shows that according to the model, the process has just reached the peak and therefore it is going to enter the declining phase of its life–cycle. One may find these forecasts too pessimistic; however, as we have explained in Section 3, the current trend is to extend the life–cycle of existing power plants from 40 to 60 years. In 2010 the IAEA reported that the majority of reactors are at least 26 years old; this means that these reactors will be shut down (at the age of 60) in 2044, which is coherent with our forecasts on

Table 10: World: ARMA (2,1) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$AR(1)$	$AR(2)$	$MA(1)$	$Mean$
1.68059	-0.84067	0.97797	-4.78023
(18.95030)	(-9.34433)	(63.98950)	(-1.83850)
[0.00000]	[0.00000]	[0.00000]	[0.07324]

Table 11: France: parameter estimates for a GBM with one exponential shock. ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.999976$ is a determination index based on cumulative data

m	p	q	c_1	b_1	a_1	R^2
20550	0.00026	0.08155	3.74580	-0.14809	15.46580	0.999976
(17571)	(0.00023)	(0.06763)	(3.25764)	(-0.17438)	(15.07830)	
(23529)	(0.00029)	(0.09548)	(4.23397)	(-0.12179)	(15.85330)	

consumption dynamics, see Figure 5(a). The alternative procedure, which is based on a Norton–Bass perspective, thus on instantaneous data under the hypothesis of a stationary trend in diffusion once the asymptote has been reached, yields the results presented in Table 9. In this case a good fitting is obtained through a simple Bass model and an ARMA (2,1) on autocorrelated residuals (see Tables 9, 10, and Figure 5(b)). According to this view, the process has just reached the asymptote and is beginning the stationary trend. Therefore both interpretations of diffusion do not predict a future growth for nuclear consumption in the world.

France is the worldwide exception in the nuclear sector. Thirty–five years ago, the French government launched the world's largest public nuclear power program in response to the oil crisis (today per capita oil consumption in France is higher than in Germany, Italy, and the UK).

A satisfactory fitting to data is achieved through a GBM with one exponential shock, $R^2 = 0.999976$ (Table 11 and Figure 6(a)). The analysis is completed with the usual ARMA refining (see Table 12).
From the analysis of the data series, we see that the process began quite slowly and increased in a dramatic way starting from 1980, as consequence of strong policy measures aimed at energy security in France, after the 1973 and 1979 oil shocks.

Table 12: France: ARMA (2,0) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$AR(1)$	$AR(2)$	$Mean$
1.37076	-0.72524	-2.92986
(10.52720)	(-5.54451)	(-0.85867)
[0.00000]	[0.00000]	[0.39539]

Table 13: France: parameter estimates for a BM on instantaneous data (Norton–Bass). ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.992539$ is a determination index based on instantaneous data

m	p	q	R^2
430.711	0.0010	0.25329	0.992539
(420.451)	(0.00056)	(0.22676)	
(440.972)	(0.00147)	(0.27982)	

The proposed model captures this acceleration through a highly positive exponential shock ($c_1 = 3.74$), started in 1980 ($a_1 = 15.46$). Interestingly, in France, the Chernobyl disaster did not have evident effects, which may be due to the fact that nuclear energy has always been quite popular in this country; reasons for popular support may be revised in a sense of national independence from foreign oil and the aim to reduce greenhouse gases. In fact, France is the second largest nuclear power consumer in the world, with 59 nuclear reactors. However, we see that, in recent years, a decline in consumption has occurred, which is coherently interpreted by our model (see Figure 6(a)). In addition, we have found that the BM is the most suitable structure in a Norton–Bass view; Table 13, Table 14 and Figure 6(b) show the results obtained. In particular, we see that neither interpretation of diffusion foresees a future growth for this process, which is, respectively, declining or going on according to a stationary trend. These results may probably make more sense once one considers that France stopped uranium mining in 2002 and that there is just one reactor under construction in the country.
Uranium mining in France started very early both for military and civil purposes; production increased until the end of the 1980s and declined sharply until 2002, when it definitely ended. After two important downgradings in 1991 and 2001, “reasonably assured” and “estimated” resources below $80\$/Kg$ U are now zero. Resource estimates increased as long as the production increased, but were followed by significant downgradings as soon as production peaked and started to decline [7]. Incidentally, this may support our choice to model the process of uranium production, rather than trying to provide direct estimates of reserves; the case of France suggests that resource assessment is related to production dynamics.
As far as reactors are concerned, according to [13], due to existing overcapacities and the average age of about 25 years of its power plants, France does not need to build any new units for a long time. The only unit under construction is Flamanville-3, started in 2007, which has encountered several problems of quality control; this has caused delays to its commercial start, which still remains unspecified.

5 Conclusion

The recent events in Japan, at Fukushima, dramatically drawn attention to the high risks connected to nuclear energy employment. Encouraged by these facts, some countries, especially in Europe, have decided to reconsider the nuclear option,

Table 14: France: ARMA (0,2) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$MA(1)$	$MA(2)$	$Mean$
-0.74500	-0.36294	-1.82392
(-4.90478)	(-2.376)	(-0.52916)
[0.00001]	[0.02213]	[0.59947]

and to reduce their share within the electricity mix. For instance, Germany has already announced the shutdown of 7 reactors, and other countries have planned stress tests on their power plants. Although the security issue legitimately plays a central role in a decision in favour or against nuclear energy, in this paper we give a complementary contribution to the debate on the theme, focusing on the evolution of dynamics of uranium extraction, reactor startups, and nuclear power consumption. Indeed, these are critical points to understand if we are really facing a nuclear renaissance.

The results obtained in our study do not seem to support such a hypothesis. Despite a recent increase, probably due to the Kazakhstan boom, the global production of uranium seems to be doomed to decline severely in the next twenty years, in accordance with the predictions of the Energy Watch Group [7]. The choice to model uranium production data to provide an indirect estimate of reserves seems particularly reasonable, considering the quite unreliable information provided on reserves, for instance in the Red Book. We foresee a declining pattern for reactor startups as well; although there are 60 reactors under construction in China, Russia, and India, giving evidence to the aggressive energy policy of these countries, it may be useful to remind that not even the 50% of similar past nuclear growth scenarios in the OECD block were eventually realized (see [6]). The analysis of parallel consumption dynamics at world and regional levels do not show a growing trend for nuclear power.

6 Appendix A

In this Appendix, we develop an analysis of nuclear power consumption dynamics in Japan and the USA which, together with France, hold the majority of reactors in the world. We will see that the results obtained confirm those presented in Section 4.

In the case of Japan, we obtained satisfactory results by applying a GBM with two exponential shocks, as confirmed by the high level of fitting, $R^2 = 0.999960$, and by the very stable estimates of all the model parameters, presented in Table 15 and Figure 7 (a). An ARMA (2,1) has been applied to autocorrelated residuals, and the results are presented in Table 19 and Figure 7 (a).

Japan is the only country to have experienced the devastations of the atomic bomb in World War II, and the use of nuclear power for civil purposes has been perceived as the peaceful answer to this fact. Today, Japan is the third largest nuclear power consumer in the world, with 54 nuclear reactors. Since the early

Table 15: Japan: parameter estimates for a GBM with two exponential shocks. ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.999960$ is a determination index based on cumulative data

m	p	q	c_1	b_1	a_1
11373	0.00019	0.11887	2.84270	-0.19031	11.08300
(8819)	(0.00011)	(0.09779)	(2.15157)	(-0.26434)	(9.86449)
(13926)	(0.00027)	(0.13995)	(3.53382)	(-0.11628)	(12.30160)
c_2	b_2	a_2	R^2		
-0.22134	-0.05875	37.14350	0.999960		
(-0.30080)	(-0.25544)	(36.31420)			
(-0.14188)	(0.13793)	(37.97270)			

Table 16: Japan: ARMA (2,1) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$AR(1)$	$AR(2)$	$MA(1)$	$Mean$
1.43086	-0.73384	1.04296	-0.12620
(13.58990)	(-6.95858)	(33.62240)	(-1.56975)
[0.00000]	[0.00000]	[0.00000]	[0.12416]

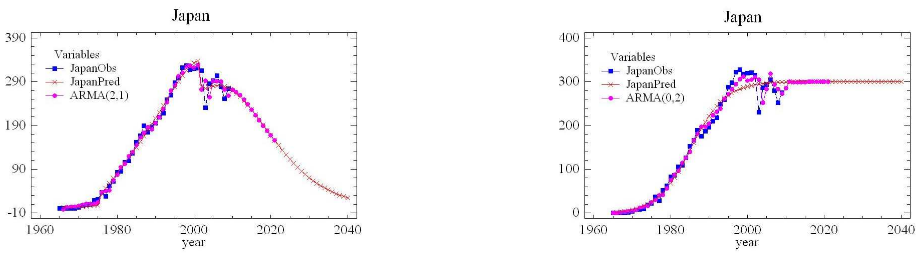
70s, nuclear power has represented a strategic solution for electricity provision in a country highly dependent on imported fuels. In particular, the proposed model identifies a positive ($c_1 = 2.84$) shock to consumption arising in 1976 ($a_1 = 11.083$), which may be reasonably interpreted as an acceleration to production/consumption of nuclear energy after the effects of the first oil shock in 1973. As we have seen, the first wave of reactor connections to the grid peaked in 1974. Instead, there is no evidence in data of negative outcomes of the Chernobyl disaster for the Japanese nuclear industry: construction of new plants continued through the 1980s, 1990s, until recent years. According to the model, a second, negative ($c_2 = -0.22$) perturbation begun in 2002 ($a_2 = 37.14$) and lasted for about two years; this may be related to a large falsification scandal starting in August 2002, with attempts to hide cracks in reactor vessels, that led to shutdown all 17 nuclear reactors of the Tokyo Electric Power Company. In the limited life–cycle hypothesis, we see that nuclear power consumption in Japan has just reached its peak and is entering the declining phase,

Table 17: Japan: parameter estimates for a BM on instantaneous data (Norton–Bass). ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.970623$ is a determination index based on instantaneous data

m	p	q	R^2
300.469	0.00191	0.22039	0.970623
(285.501)	(0.00055)	(0.17425)	
(315.438)	(0.00328)	(0.26653)	

Table 18: Japan: ARMA (0,2) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$MA(1)$	$MA(2)$	$Mean$
-0.60586	-0.45486	-0.52576
(-4.30963)	(-3.19432)	(-0.10354)
[0.00009]	[0.00265]	[0.91802]



(a) (b)

Figure 7: Nuclear power consumption in Japan: GBM with two exponential shocks and ARMA (2,1) in a life–cycle perspective (a), BM and ARMA (2,1) in a Norton–Bass perspective

see Figure 7(a). It is too soon to foresee the effects of the tsunami that occurred in early 2011 on Japanese nuclear consumption, which has also caused enormous damage to four power plants, with the release of radioactive emissions. At best, we may expect that the trust in nuclear power by the Japanese will be tried by these events, with a likely acceleration of the consumption decline evidenced in most recent years. The results of the second application, based on the Norton–Bass view, are presented in Table 17 and Figure 7. We may see that, according to a simple BM fitting to instantaneous data of adoption, the process has just started the stationary trend. Again, we observe that the two modelling choices do not support the hypothesis of a future growth for nuclear consumption in Japan.

The USA has more operating nuclear power plants than any other country in the world, with 104 reactors in operation. Despite this large number of operating reactors, the number of cancelled projects is even larger (138 units). The lack of new reactor projects means that around one third of the current power plants will have operated for at least 40 years by 2015. Not surprisingly, the USA nuclear power industry remains highly successful in two main areas, namely increased output from existing reactors and plant life extensions. The data show that in the USA consumption dynamics experienced two accelerations in the mid 1970s and 1980s. To describe this series we have selected a GBM with two exponential shocks, which is able to capture these two accelerations in a satisfactory way, $R^2 = 0.999984$. The first shock, a very strong one ($c_1 = 10.81$), occurred around 1974 ($a_1 = 8.55$), right

Table 19: The USA: parameter estimates for a GBM with two exponential shocks. ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.999984$ is a determination index based on cumulative data

m	p	q	c_1	b_1	a_1
43078	0.00032	0.00633	10.81250	-0.00163	8.55746
(23466)	(0.00015)	(0.00233)	(7.22909)	(-0.02440)	(8.19703)
(62690)	(0.00050)	(0.01032)	(14.39600)	(-0.02113)	(8.91789)
c_2	b_2	a_2	R^2		
4.00959	-0.21460	22.52170	0.999984		
(1.33756)	(-0.32418)	(21.95320)			
(6.68162)	(-0.10502)	(23.0901)			

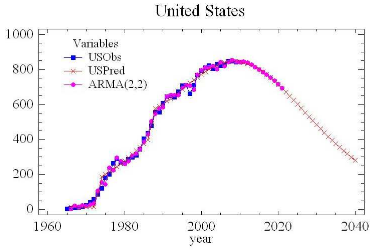
Table 20: The USA: ARMA (2,0) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$AR(1)$	$AR(2)$	$Mean$
1.37076	-0.72524	-2.92986
(10.52720)	(-5.54451)	(-0.85867)
[0.00000]	[0.00000]	[0.39539]

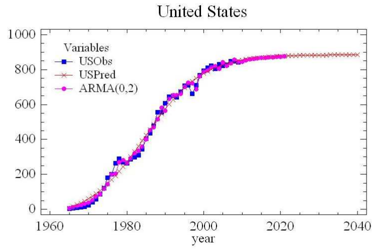
after the first oil shock, when the first wave of reactor startups reached its peak. The second one, less intense than the first, but also very strong ($c_2 = 4.00$), arose in 1987 ($a_2 = 22.57$) and may be correlated to the second wave of reactor startup, which peaked in 1984. Completed with an ARMA (2,0), the GBM interprets the consumption series as if it had just reached the peak, and consequently foresees a future decline. This result should be probably considered with caution, recalling that the Bass models naturally tend to close a process, since they are based on a single and finite life–cycle hypothesis. Under a Norton–Bass view of diffusion, the process is well described with a BM, according to which the process is just entering the stationary trend (see Table 21, 22). This may be coherent with the life extension decided in 2009 for half of the operating power plants. With respect to the uranium supply situation in the USA, it will be useful to remember that only 8% of the uranium needs of the USA are coming from their own mines. Currently,

Table 21: The USA: parameter estimates for a BM on instantaneous data (Norton–Bass). ( ) marginal linearized asymptotic 95% confidence limits. $R^2 = 0.990013$ is a determination index based on instantaneous data

m	p	q	R^2
884.928	0.00788	0.12606	0.990013
(844.963)	(0.00617)	(0.10612)	
(924.893)	(0.00960)	(0.14599)	



(a)



(b)

Figure 8: Nuclear power consumption in the USA: GBM with two exponentials shock and ARMA (2,0) in a life–cycle perspective (a), BM and ARMA (0,2) in a Norton–Bass perspective

Table 22: The USA: ARMA (0,2) on autocorrelated residuals; ( ) t-statistic, [ ] p value

$MA(1)$	$MA(2)$	$Mean$
-0.90978	-0.33392	-2.19308
(-6.30764)	(-2.33460)	(-0.31462)
[0.00000]	[0.00000]	[0.75460]

50% of uranium needs in the USA are satisfied by imports from Russia, thanks to the "Megatons to Megawatts Program", which will stop at the end of 2013. In [6], it is fairly observed that this is especially remarkable since energy independence has been one of the major aims of all American governments since many years.

Commercial uranium production in the USA started in 1947 and reached its peak in 1980, followed by a steep decline. Similar to what was seen in France, in the USA a strong correlation is seen between declining production and downgraded resources, which raises strong doubts about the reliability of reporting practices of known resources (see [7]).

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