The diffusion of nuclear energy in some developing and graduated developing countries

Alessandra Dalla Valle and Claudia Furlan

Abstract The electric power demand is increasing worldwide and, in the last years, the energy policy focused on expanding the nuclear power, especially in the developing countries. One of the key points is the depletion time of uranium. Indeed, would be the uranium resources sufficient to meet projected nuclear energy that are particularly challenging in the developing countries? An analysis of nuclear energy diffusion of some graduated developing countries (Slovak Republic and South Korea) and developing countries (Ukraine, China, Bulgaria, and India) is performed. The conclusion is that with the actual energy policy, with the estimated depletion time of uranium, and considering 50 years as a reasonable life-time for reactors, it seems not believable to keep both working the already existing reactors and even the projected ones of the analyzed countries only.

Key words: Diffusion models; Bass Models; Nuclear Energy; Reactors; Developing Countries

1 Introduction

One of the most difficult challenges of the future will be to keep balance between energy demand for economic and social progress and the consequent environmental and social-political impact deriving from this demand. The diffusion of a model of western development in countries such as China and India, is one of the reasons of the increase of energy demand. We focused upon the expansion of nuclear power demand especially in the developing countries that now represent the most important supporters of the nuclear projects and we discuss the question if uranium resources would be sufficient to front the increasingly needs in breakable and challenging balances of developing countries governments. In particular, we analyze the developing countries Ukraine, China, Bulgaria, India, and also the graduated developing countries Slovak Republic and South Korea, that were considered developing countries until recently[1]. In the field of innovation studies technological diffusion has a long scholarship starting in the 1960's with the works of [2] and [6]. In this context, the Bass Model has been widely used, for its properties and parameters' meaning. In this paper, we use the Generalized Bass Model (GBM) proposed by [1]:

Alessandra Dalla Valle and Claudia Furlan
Department of Statistical Sciences, Padua e-mail: alevalle,furlan@stat.unipd.it

[1] In the following, for brevity, we will refer to all of them with the word "developing" countries.

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

where m is the potential market (i.e., the maximum deliverable nuclear energy), p and q are the parameters referred to the quota of innovators and imitators (i.e., the governments of the countries), respectively, and $x(t)$ is an integrable function that oscillates around 1.

Guseo & Dalla Valle [3] proposed a specification of $x(t)$ that was useful for depicting and modelling strategic interventions that significantly modify the diffusion of energy products, e.g., oil, gas, wind power [4], through exogenous exponential and rectangular shocks. The mathematical form of the *exponential* shock is $x(t) = 1 + c_1 e^{b_1(t-a_1)} I_{[t \geq a_1]}$, where $I_{[t \geq a_1]}$ is a 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. 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: $x(t) = 1 + c_1 I_{[a_1 \leq t \leq b_1]}$ 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.

The mathematical representation of, respectively, two exponential shocks and one rectangular shock is the following:

$$x(t) = 1 + c_1 e^{b_1(t-a_1)} I_{[t \geq a_1]} + c_2 e^{b_2(t-a_2)} I_{[t \geq a_2]} + c_3 I_{[a_3 \leq t \leq b_3]}. \tag{2}$$

2 Results

Developing countries.

In this section, we focus only on South Korea, China, and India (see Fig. 1 for the fitted models for all the developing countries). At the moment, the South Korea has 6 nuclear power plants with a total of 21 operational reactors and 5 under construction; India has 8 nuclear plants with 20 operational reactors and 5 reactors under construction; China has 4 nuclear plants with 13 operational reactors and 1 reactor under construction, and has planned other 26 new reactors under construction, for a total of other 9 new plants.

The GMB for South Korea includes one rectangular and one exponential shock (Equation (2) without the second exponential shock). The rectangular shock is detected of a great intensity ($c_3 = 1.9417$) between 1985 and 1992 and it is explained by the commercial operation of 6 reactors. The exponential shock was found to be positive ($c_1 = 0.7981$), arising around 1992, 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. The model suggests that South Korea is in the middle of the life-cycle and has already reached its peak in 2009.

The GMB for China includes one rectangular and one exponential shock (Equation (2) without the second exponential shock). The rectangular shock is negative detected of a small intensity ($c_3 = -0.3420$) between 1998 and 2002/2003. It can

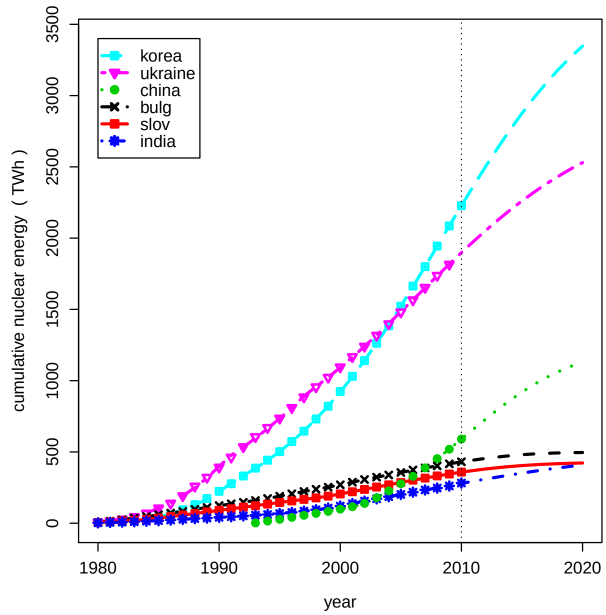

Fig. 1 Observed and predicted cumulative nuclear energy (TWh).

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 (4 only in 2002). Indeed, this second phase has been catched by the exponential shock located around 2004/2005, and its effect has been completely absorbed in time (b_1 is negative). China has had a considerable nuclear expansion rate after the second shock round 2004, and GBM estimates suggests that it is now in the middle of the life-cycle.

The proposed GMB for India includes 2 exponential shocks (Equation (2) without the rectangular shock). The first has a negative impact around 1990, while the second a positive one around 2000/2001. Both has been completely absorbed in time. 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 afterwards 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 that will be produced in the future, since it does not catch the particular pattern of the last three years. The reason lies again on the scarcity of uranium Russian supply in India in 2004-2006, that was overcome in 2008 with the sign of a new agreement.

Uranium.
Uranium is produced in about 20 different countries. In 2008, Australia, Canada, Namibia, and Kazakhstan accounted for 69% of the world production. We apply a GBM model since uranium is a finite resource, with a limited production life-cycle. Data consist of annual world production of uranium (tons) from 1945 to 2009. The proposed GMB identifies three negative shocks (Equation (2)), one rectangular and two exponentials. 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 arm 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 the nuclear plant development in the 70's-80's. The third shock is still positive, it arises around 1991, it is positive and completely absorbed in time. The depletion time of uranium has been estimated round 2045. Total extractible uranium is estimated to be 3 347 710 tU. Since requirements of uranium amount to 2 464 185 tU in 2009, it means that only the 26% of the total uranium is still usable (883 525 tU). Probably the total extractible uranium should be slightly higher, since new mines were opened in Kazakhstan in the last few years, but it is known that the extractive capacity of those mines is limited in time.

World reactor uranium requirements by the year 2035 are projected to increase from 40% to 120%, with respect to 2009 [5]. If we consider the uranium requirement of 61 805 tU in 2009, the predicted uranium requirement in 2035 would then be between 86 527 tU and 129 790 tU (+40% and +120%, respectively). Translating this information into years, uranium would last 37 years in the low case, and 25 years in the high case.

Based on AIEA reactor data, it is known that of the currently 442 operational reactors, supposing a mean life time of 50 years, 196 will be still working in 2035. At that time, probably 108 reactors will be operational in the developing countries, while 153 in the rest of the world. Considering the uranium requirements of 2035 provided by [5], the developing countries, that will have almost one half of the operational reactors in the world, will require between the 58% and 77% of the estimate available uranium (883 525 tU). It is apparent that the expansion projected by at least some developing countries cannot be fully believed.

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