Are there any effects of Fukushima accident on the diffusion of nuclear energy?

L'incidente di Fukushima ha avuto effetti sulla diffusione dell'energia nucleare?

Claudia Furlan, Mariangela Guidolin, Renato Guseo

Abstract The year 2012 registered a decline of nuclear power consumption in several countries such as the US, France, Germany, and other OECD members. Was it a post-Fukushima outcome? We focus on the nuclear consumption leaders – the US, France and Germany – and explore, through diffusion models, whether and to what extent Fukushima had an effect on their consumption dynamics. In particular, we compare the evolutionary behavior estimated with the entire time series and that obtained by excluding the last two observations (2011 and 2012): how would the forecasts have been before Fukushima? The results show that nuclear energy policy of these countries does not seem to be affected by the accident: nuclear technology is being dismissed with different speeds and timing due to rising costs in risk management and possible shortages in Uranium 235 supply.

Abstract *Nell'anno 2012 si è registrato un declino del consumo di energia nucleare in vari paesi come Stati Uniti, Francia, Germania. Può trattarsi di una conseguenza dell'incidente di Fukushima? I consumi di questi tre paesi sono stati analizzati tramite modelli di diffusione per comprendere se e in che misura tale evento abbia avuto un effetto. In particolare, come sarebbero state le previsioni prima dell'incidente di Fukushima? A questo scopo sono state confrontate le dinamiche evolutive stimate con l'intera serie dei dati ed escludendo gli anni 2011 e 2012. I risultati suggeriscono che le politiche di energia nucleare di questi paesi non sembrano essere state condizionate: la dismissione della tecnologia nucleare, dovuta a costi crescenti per la sicurezza e a una limitata disponibilità di Uranio 235, si sta sviluppando con differenti velocità e tempistiche.*

Key words: nuclear power, energy policy, diffusion, variable market potential

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1 Introduction

Of all the forms of energy employed to generate electricity, nuclear is probably the most concerned by safety issues. The history of commercial use of nuclear fission dates back to the 1950s and has been characterized by three major accidents. The first one, occurred in 1979 at Three Mile Island (USA), fortunately had a quite limited effect. Conversely, the accident that produced catastrophic consequences for the nuclear fallout in Western USSR and Europe was that of Chernobyl in 1986, whose effects on the environment and on human health are still being accounted for. The Chernobyl disaster is considered the worst ever and has been classified at level 7 on the INES scale (maximum level). The other accident classified at level 7 is that of Fukushima (Japan) occurred in March 2011. The Fukushima accident implied that Japan, from being the world's third largest nuclear power generator fell down to the 18th position between 2010 and 2012 due to the shutdown of all its reactors [8]. According to the IAEA-Pris database, currently in Japan 9 reactors result shutdown, while 50 are still operational, even though most of them have not generated electricity for years [8]. Certainly the disaster changed in a radical way the japanese public opinion about this energy source. Moreover, it is argued that this was responsible for reconsideration of nuclear power policy in many countries. In particular, many questions raised about the prevailing choice to implement the uprating process, that is technical alternations and lifetime extensions at existing plants. As reported by the BP Statistical Review of World Energy, the year 2012 registered a decline of nuclear power consumption in several countries such as the US, France, Germany, and other OECD members. Was it a post-Fukushima outcome?

Setting apart the case of Japan, which may be considered exceptional, we focus on the nuclear consumption leaders – the US, France and Germany – and explore, through diffusion models, whether and to what extent Fukushima had an effect on consumption dynamics of these. In particular, we compare the evolutionary behavior estimated with the entire time series and that obtained by excluding the last two observations (2011 and 2012): how would the forecasts have been before Fukushima?

2 Models

Consumption dynamics of nuclear power may be described through diffusion models, like the Bass model, BM. An extension of the BM which assumes a time dependent market potential $m(t)$ has been proposed by Guseo and Guidolin [6] producing a model for cumulative consumption $z(t)$ that we denote here as the Guseo–Guidolin model, GGM,

$$z(t) = \sqrt{\frac{1-e^{-(p_c+q_c)t}}{1+\frac{q_c}{p_c}e^{-(p_c+q_c)t}}}\;\frac{1-e^{-(p_s+q_s)t}}{1+\frac{q_s}{p_s}e^{-(p_s+q_s)t}}, \tag{1}$$

where p_c, q_c denote the communication parameters generating the non-constant market potential, and p_s, q_s express the dynamics of adoption. Notice that Equation

Table 1 Estimates and marginal linearized asymptotic 95% CI (into brackets) for GGM fitted to the US and France, and for GGBM fitted to Germany. The entire time series have been used. R^2, squared multiple partial correlation coefficient $\tilde{R}^2$, and corresponding F are provided [6].

Par.	US	France	Germany
K	35795	15656	5561
	$(31598, 39992)$	$(15288, 16024)$	$(5343, 5778)$
p_c	0.00034	0.00015	0.00004
	$(0.00025, 0.00044)$	$(0.00014, 0.00017)$	$(-0.00007, 0.00015)$
q_c	0.11439	0.14545	0.18971
	$(0.09864, 0.13015)$	$(0.14151, 0.14938)$	$(0.13391, 0.24551)$
A_c			0.65957
			$(0.35108, 0.96804)$
p_s	0.00947	0.00096	0.00032
	$(0.00818, 0.01077)$	$(0.00083, 0.00108)$	$(-0.00008, 0.00073)$
q_s	0.13803	0.25631	0.30492
	$(0.11933, 0.15673)$	$(0.24688, 0.265734)$	$(0.24964, 0.36020)$
A_s			0.55301
			$(0.36097, 0.74505)$
R^2	0.99991	0.99998	0.99998
$\tilde{R}^2$	0.9181	0.9913	0.9895
F	241	2451	964

(1) may be thought of as a product of two distribution functions resulting, therefore, in a new distribution. Following this suggestion we may modify the GGM by introducing one or two extensions, based on parameters A_c and A_s, in the two factors related to the variable potential and/or to the adoption component to account for heterogeneity effects, through the Bemmaor's approach [1]. The new cumulative model characterized by heterogeneity effects, GGBM, is

$$z(t) = \sqrt{\frac{\left(1-e^{-(p_c+q_c)t}\right)}{\left(1+\frac{q_c}{p_c}e^{-(p_c+q_c)t}\right)^{A_c}}\,\frac{\left(1-e^{-(p_s+q_s)t}\right)}{\left(1+\frac{q_s}{p_s}e^{-(p_s+q_s)t}\right)^{A_s}}}, \qquad t \geq 0, \tag{2}$$

where $A_c, A_s, p_c, q_c, p_s, q_s > 0$. In particular, high values of A_c and A_s denote heterogeneous behavior among agents, especially, within imitators, in communication and adoption, and determine a delay. Vice versa, small values of A_c and A_s , $<< 1$, denote a high concentration of adoptions at the beginning of the process.

3 Results and concluding remarks

The life-cycle analysis of nuclear consumption is restricted, as mentioned in Sec. 1, to the US, France and Germany. We have chosen these three countries because,

among the leading countries, they have a long history in nuclear energy and they have already peaked. In the diffusion contest, this allows the models to be more reliable and predictive. We applied, for each country, the GGM and the GGBM. A test for nested models, with a procedure based on the reduction of the residual deviance [4], is applied to select the best model between GGM and GGBM. Results are shown in Table 1: the model adequacy coefficients, $\tilde{R}^2$ and F [6], highlight the great improvement with respect to the BM.
The selected model is then fitted again, by excluding the data of 2011 and 2012. For each country, the two evolutionary patterns are compared. Data about nuclear consumption is provided by BP, while information about the commercial operation state of reactors is provided by IAEA PRIS.

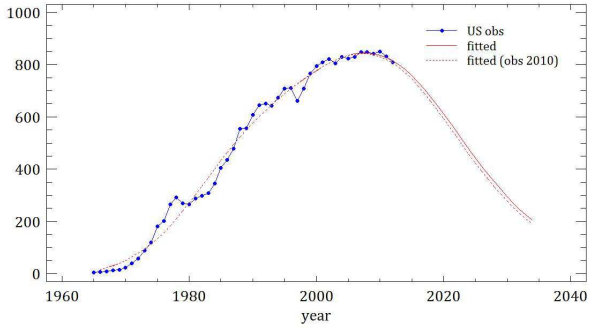

Fig. 1 United States: annual nuclear consumption (TWh). Solid line corresponds to the fitted values obtained with estimates of Table 1. Dotted line corresponds to the fitted values obtained by excluding 2011 and 2012.

The US

For the US, the GGM results to be the best parsimonious model. The parameter estimates are stable, as shown by the marginal linearized asymptotic 95% CI, and the goodness-of-fit is overall good (Table 1). The model cannot detach very well the incredible nuclear expansion before the 1979 Three Mile Island accident, but it is rather precise in the second half of the time series, especially in the last decade.

The difference in terms of estimated evolutionary behavior by excluding what happened after Fukushima (years 2011 and 2012) is negligible (Fig. 1), and marginal CIs are essentially overlapping. The US did not change their nuclear policy after Fukushima, except by paying a bigger attention to safety especially for the 60 of the 104 reactors which have a operating license extension. However, safety has a cost and this contributed to make the nuclear energy less economically competitive with respect not only to wind power, but also to natural gas at a time when gas prices have fallen. For these reasons, in 2013 four aging reactors were permanently shut down before their licences expired. The uprating, which had a considerable economic advantage in the past over new reactor building, is not so far considered (except for a few units), since the uprating leads to lower levels of safety and higher levels of operating costs [8].

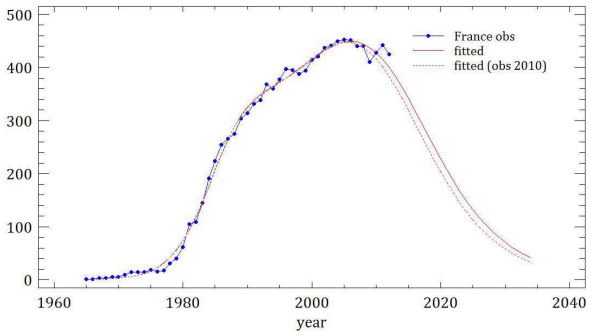

Fig. 2 France: annual nuclear consumption (TWh). Solid line corresponds to the fitted values obtained with estimates of Table 1. Dotted line corresponds to the fitted values obtained by excluding 2011 and 2012.

France

Also for France, the GGM results to be the best parsimonious model. The parameter estimates are stable, the marginal linearized asymptotic 95% CI are well identified, and the goodness-of-fit is very good (Table 1). As Fig.2 shows, the model captures very well the behavior of the data until the very last few observations. The big fall in national consumption in 2009, followed by a substantial restart in 2010-2011 and then by a small fall in 2012, causes an uncertainty in modeling. The model can only pass through these observations as a mean behavior of what happened. The pattern of these data is too recent to be modeled with a high degree of precision. Probably, at the time the value of 2013 will be available, the model will predict a more precise shape of the life cycle than it does now. Nevertheless, previous concerns are not so critical, in fact, also for France, the difference in terms of estimated evolutionary behavior by excluding what happened after Fukushima is negligible (Fig. 2). No plants have been closed in France after 2011. The effect of Fukushima is still on safety and in fact the government's intention is to upgrade the protection of vital functions in all its nuclear reactors. Safety has a cost, but nuclear electricity in France remains cheaper especially with respect to the US [2]. In fact, in February 2012 the existing reactors received the license for being operating beyond 40 years. The Court of Audit said that this was the best option since new nuclear capacity, or other forms of energy, would be more costly and available too late.

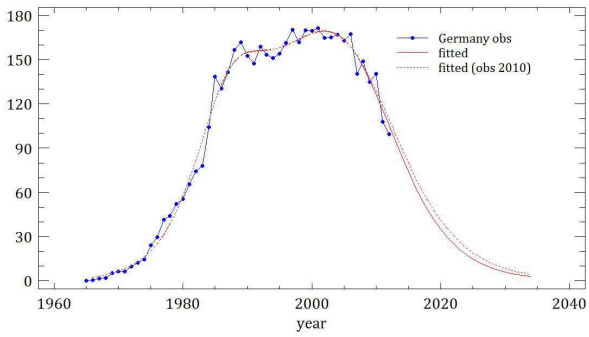

Fig. 3 Germany: annual nuclear consumption (TWh). Solid line corresponds to the fitted values obtained with estimates of Table 1. Dotted line corresponds to the fitted values obtained by excluding 2011 and 2012.

Germany

For Germany, the GGBM has been selected. The fitting is very good (Fig. 3), and the parameter estimates are stable, except for p_c and p_s that show a slight instability (Table 1). The two coefficients A_c and A_s are less than 1 and this indicates that in Germany there has been a kind of homogeneous behavior in the access and in the use of the nuclear technology, with a good maintenance service, that has lead to regularity in energy supply.

Also excluding the last two observations, the GGBM is very stable in forecasting the evolutionary behavior. It seems that what happened in 2011 and 2012 did not change the forecast of the life cycle of nuclear energy in Germany. In fact, the nuclear phase-out was planned in 2002 with a final retreat planned for 2022. In October 2010, the government decided to modify the phase-out plan, extending the reactor licenses of 12 years. However, after a few months, less than a week after the Fukushima accident, the government came back to the nuclear policy signed in 2002. In addition, the government decided to shut-down the 8 oldest reactors (on the 17 existing operating reactors), before their licences expired, causing a loss of 30% in nuclear power generation [7]. This halt can be seen in Fig. 3 with the data of 2011. Germany compensates the loss of nuclear power increasing the electricity production by renewable energy, and reducing the domestic electricity demand [7]. In summary, Fukushima had a slight effect of accelerating the phase-out of the oldest reactors for increasing the safety level, but essentially in agreement with the retreat plan signed one decade before.

As a concluding remark, nuclear energy policy of the leading countries does not seem to be affected by the Fukushima accident: nuclear technology is being dismissed with different speeds and timing due to rising costs in risk management and possible shortages in Uranium 235 supply. For further details, see Guidolin and Guseo [5] and Dalla Valle and Furlan [3].

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