Modelling competition between nuclear power and renewable energy technologies: some results and forecasts for Germany

Mariangela Guidolin*
University of Padua, Department of Statistical Sciences, Padua, Italy - guidolin@stat.unipd.it

Renato Guseo
University of Padua, Department of Statistical Sciences, Padua, Italy - renato.guseo@unipd.it

Abstract

Modelling the diffusion processes of competing technologies is a theme of great interest in many socio-economic contexts. Univariate innovation diffusion models fail to account for competition and substitution dynamics, whose understanding may be crucial both for policy implications and forecasting. In this paper we propose the application of two diffusion models for a duopolistic competition, unrestricted and standard UCRCD, to the annual time series of consumption of nuclear and renewables (wind and solar energy) in Germany. The data suggest a substitution effect between nuclear and renewables. Interestingly, the obtained results confirm this first conjecture and show that renewables exerted a significant and measurable effect in determining the observed decline of nuclear power consumption.

Keywords: competition modelling; renewable energy technologies; energy transition; word-of-mouth

1. Introduction

Modelling and forecasting the diffusion of an innovation over time in a socioeconomic system is a theme that has called the attention of researchers since the 1960s'. A huge body of scientific literature on this topic has been produced by scholars pertaining to various disciplines, in order to understand what are the drivers of such processes and try to predict their evolution in space and time. Typical applications of diffusion models have been durable goods, ICTs, pharmaceuticals, cultural goods and services: for this reason, a relevant contribution in terms of models and research insights has been given by the quantitative marketing literature. Comprehensive reviews of diffusion models in marketing may be found for instance in Meade & Islam (2006) and Peres et al. (2010).
More recently, there has been an increasing interest on the use of diffusion models in the energy sector in order to forecast the evolution of different energy sources, with a growing attention towards renewable energy technologies (RETs). See for instance Davies & Diaz-Rainey (2011), Meade & Islam (2015), Usha Rao & Kishore (2015). The adoption of RETs is essential to gain sustainability goals and to face the energy independence issue connected with fossil fuels depletion.
The Bass models, in standard (Bass, (1969)) and generalized (Bass et al. (1994)) versions, still represent an essential reference for modelling univariate processes. In particular, the GBM has proven very useful when diffusion is highly influenced by external interventions able to alter its speed, such as incentive schemes and policies. Several applications concerning both non-renewable and renewable energy sources have highlighted its central role, see for instance Dalla Valle & Furlan (2014), Guidolin & Guseo (2012), Guidolin & Mortarino (2010), Guseo (2011), Guseo et al. (2007).
A critical point of such applications is the partial consideration of the socio-economic and technological context in which diffusion occurs: in particular, the use of univariate models does not account

for competition and substitution dynamics that are crucial for understanding how and why energy transitions may develop. As highlighted in Grubler (2012) "technological and associated institutional/organizational transformations in energy end-use are the fundamental drivers of historical energy transitions". This fact may help explain the different speeds characterizing these processes: as pointed out by Arthur (1989), technological "lock-in" is a well-known issue.

As competition and substitution are central aspects to be considered to analyze energy transitions, the use of multivariate diffusion models appears a necessary step. The literature on this kind of models is quite recent, but some important contributions have been proposed by Guseo & Mortarino (2010), Guseo & Mortarino (2012), Guseo & Mortarino (2014), Krishnan et al. (2000), Savin & Terwiesch (2005). Specifically, these models describe a duopolistic competition with sequential market entry. In Guseo & Mortarino (2012) and Guseo & Mortarino (2014) changes in the first entrant parameters due to competition are allowed. Moreover, the models proposed in Guseo & Mortarino (2014) , namely standard UCRCD and unrestricted UCRCD, allow for a general structure of the word-of-mouth, according to which each competitor is influenced by *within* and *cross* effects.

In this paper we present the results of the application of standard and unrestricted UCRCD to the competitive dynamics occurring between nuclear power and renewables (solar and wind) in Germany. The case of Germany is particularly interesting for the so-called "Energiewende" (the German expression for energy transition) whose key policy document was published in September 2010, six months before the Fukushima nuclear accident: in fact, the two major points of this document were the nuclear phaseout and the growth of renewables.

The paper is structured as follows: in Section 2 we present the models for competition employed, unrestricted and standard UCRCD, in Section 3 we describe some aspects for model estimation, and in Section 4 we illustrate the application to the energy sector in Germany. Some concluding remarks are contained in Section 5.

2. A general model for competition: UCRCD

The general model for competition proposed in Guseo & Mortarino (2014), UCRCD, considers a duopoly where two concurring technologies, entering the market at different times, have a market potential that may take different levels: m_a, the market potential of the first entrant in the stand-alone phase, and m_c, the global or category potential under competition. The residual market $m - z(t)$ is assumed to be a common target for each competitor, with $z(t) = z_1(t) + z_2(t)$ denoting common cumulative adoptions and $z_i(t), i = 1, 2$ the cumulative sales of technology i. The second competitor enters the market at time $t = c_2$ with $c_2 > 0$. The model is a system of differential equations where $z_1'(t)$ and $z_2'(t)$ indicate instantaneous adoptions of the first and of the second technology, respectively, and I_A is an indicator function of event A,

$$
\begin{aligned}
z_1'(t) &= m\Bigg\{ \left[p_{1a} + q_{1a}\frac{z(t)}{m}\right](1 - I_{t>c_2}) \\
&\quad + \left[p_{1c} + (q_{1c}+\delta)\frac{z_1(t)}{m} + q_{1c}\frac{z_2(t)}{m}\right] I_{t>c_2} \Bigg\} \left[1 - \frac{z(t)}{m}\right], \qquad (1)\\
z_2'(t) &= m\left[p_2 + (q_2 - \gamma)\frac{z_1(t)}{m} + q_2\frac{z_2(t)}{m}\right]\left[1 - \frac{z(t)}{m}\right] I_{t>c_2}, \\
m &= m_a(1 - I_{t>c_2}) + m_c I_{t>c_2} \\
z(t) &= z_1(t) + z_2(t) I_{t>c_2}.
\end{aligned}
$$

We may observe that, as long as $t \leqslant c_2$ and the second concurrent has not yet arrived, $z_1'(t)$ is described through a standard Bass model with parameters p_{1a}, q_{1a}, and m_a. When $t > c_2$, both technologies exist in the market and evolve according to their own trajectories, which are influenced by competition. The first is characterized by new parameters: the innovation coefficient under competition, p_{1c}, and the imitative one, referred to the word-of-mouth, which is split into two parts, the *within* imitation coefficient $q_{1c}+\delta$, modulating technology-specific adoptions through the relative knowledge z_1/m, and the *cross* imitation one, q_{1c} which is powered by z_2/m and measures the effect, in terms of positive or negative word-of-mouth, of the second on the first. The second concurrent has three corresponding parameters: the innovation coefficient p_2, the *within* imitation coefficient q_2, and the *cross* imitation coefficient $q_2 - \gamma$, which measures the effect, in terms of positive or negative word-of-mouth, of the first on the second. In this most general case, divide parameters δ and γ are assumed to be possibly different, and the implicit model (that does not admit a closed-form solution) is called *unrestricted* UCRCD (unbalanced competition and regime change diachronic model). Under the weak restriction $\delta = \gamma$, the model takes a reduced form, called *standard* UCRCD, see Guseo & Mortarino (2014), and is characterized by a closed-form solution. The constraint $\delta = \gamma$ assumes a symmetric behavior between the two competitors, so that the divide between within- and cross-word-of-mouth is the same in both: this implies a substantial symmetry between the two technologies, so that what is lost by one is exactly gained by the other.

3. Statistical inference and estimation

The statistical implementation of the models presented in previous section is based on nonlinear least squares (NLS), (see Seber & Wild (1989)), under a convenient stacking of the two submodels; in particular, we may consider the structure of a nonlinear regression model

$$w(t) = \eta(\beta, t) + \varepsilon(t), \tag{2}$$

where $w(t)$ is the observed response, $\eta(\beta, t)$ is the deterministic component describing instantaneous or cumulative processes, depending on parameter set β and time t, and $\varepsilon(t)$ is a residual term, not necessarily independent identically distributed (i.i.d.) The performance of an extended model, m_2, compared with a nested one, m_1, may be evaluated through a squared multiple partial correlation coefficient $\tilde{R}^2$ in the interval $[0; 1]$, namely,

$$\tilde{R}^2 = (R^2_{m_2} - R^2_{m_1})/(1 - R^2_{m_1}), \tag{3}$$

where $R^2_{m_i},\ i = 1, 2$ is the standard determination index of model m_i.
The $\tilde{R}^2$ coefficient has a monotone correspondence with the F-ratio, i.e.,

$$F = [\tilde{R}^2(n - v)]/[(1 - \tilde{R}^2)u], \tag{4}$$

where n is the number of observations, v the number of parameters of the extended model m_2, and u the incremental number of parameters from m_1 to m_2. Under strong conditions on the distributional shape of the error term $\varepsilon(t)$, particularly i.i.d. and normality, the statistic F-ratio is a Snedecor's F with u degrees of freedom for numerator and $n-v$ degrees of freedom for denominator, $F \sim F_{u,n-v}$.

4. Competition between nuclear power and RETs: the case of Germany

In this section we present the results of the application of the UCRCD models (standard and unrestricted) to the competitive dynamics between nuclear power and renewable energy technologies, namely wind and solar, in Germany. We have chosen these sources of energy because they are the non fossil fuel based alternatives for the generation of electricity. In June 2011 the German parliament decided to phase-out nuclear power by 2022 and to generate at least 60% of electricity from renewable sources, mostly wind and solar, by 2050.

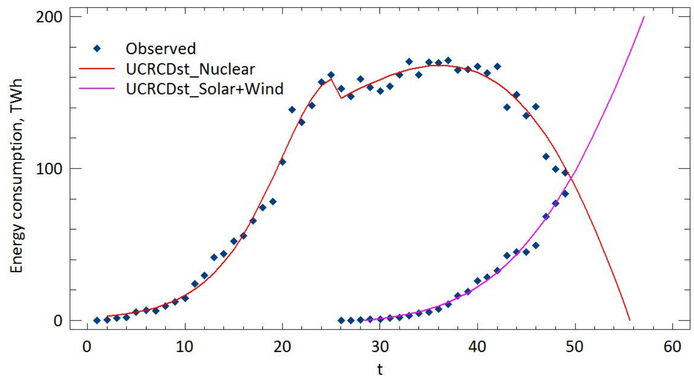

Figure 1: Annual consumption of nuclear power and renewables (wind and solar together) in TWh and forecasts with standard UCRCD model.

Table 1: Parameter estimates of unrestricted UCRCD model with $\delta \neq \gamma$; ( ) marginal linearized asymptotic 95% confidence limits. Estimates performed on instantaneous data.

m_a	p_{1a}	q_{1a}	m_c	q_{1c}	R^2
3302.95	0.00099	0.20089	50632	-0.21492	0.994538
(2779.2)	(0.00009)	(0.18409)	(-236203)	(-0.31456)	
(3826.71)	(0.00188)	(0.21768)	(337467)	(-0.11528)	
q_2	δ	p_{1c}	p_2	γ	D-W
0.13636	0.23575	0.00238	-0.00021	0.13056	2.04978
(0.01639)	(0.10476)	(-0.01096)	(-0.00150)	0.00976	
(0.25633)	(0.36673)	(0.01573)	(-0.00107)	0.25135	

Table 2: Parameter estimates of standard UCRCD model with $\delta = \gamma$; ( ) marginal linearized asymptotic 95% confidence limits. Estimates performed on instantaneous data.

m_a	p_{1a}	q_{1a}	m_c	q_{1c}	R^2
3302	0.00099	0.20089	10814	-0.23819	0.994059
(2761)	(0.00006)	(0.18351)	(8867)	(-0.27325)	
(3844)	(0.00191)	(0.21826)	(12760)	(-0.20314)	
q_2	δ	p_{1c}	p_2	γ	D-W
0.28903	0.28903	0.00886	-0.00040	-	1.89329
(0.24503)	(0.24503)	(0.00776)	(-0.00162)	-	
(0.33303)	(0.33139)	(0.00996)	(-0.00080)	-	

Table 3: Within product and cross product WOM effects in standard UCRCD model.

	UCRCD $\delta = \gamma$	
	Nuclear	RETs
Within WOM	0.048143	0.289034
	$(q_1 + \delta)$	(q_2)
Cross WOM	-0.238197	0.002694
	(q_1)	$(q_2 - \delta)$

These are two major points of the so-called "Energiewende" (energy transition in german) which represents a revolution in the German energy policy, with a substantial change from centralized to distributed generation. Here we analyze the time series of consumption (in TWh, data source: BP Statistical Review of World Energy 2014) from 1965 to 2013 for nuclear power, from 1990 to 2013 for wind and from 2000 to 2013 for solar. Specifically, we decided to put together the series of wind and solar consumption and consider them as renewable technologies as a whole. The data show that nuclear power has been experiencing an evident decline since 2010, while wind and solar have been steadily growing. In addition, there seems to be substitution effect between nuclear and renewables, whose relevance may be estimated through the UCRCD models. At a first step we applied the unrestricted UCRCD to instantaneous data, whose results are summarized in Table . The model reaches a very high level of global fitting, $R^2 = 0.994538$, and all parameter estimates are very stable, except for a slight instability of the market potential under competition m_c. For comparison purposes we estimated the standard UCRCD, whose results are summarized in Table 2 and Figure 1. Also in this case the model reaches a very high level of global fitting, $R^2 = 0.994059$, and all parameter estimates are very stable. The value of the squared multiple partial correlation coefficient $\tilde{R}^2 = 0.08$ and of the corresponding F-ratio, $F = 5.47$, suggest that the extension implied by the unrestricted UCRCD is not really significant, so that the standard UCRCD has been chosen as the best modelling option. A confirmation to this point comes from the corresponding confidence intervals of δ and γ. The interpretation of parameters gives very interesting insights on the competitive dynamics occurring between nuclear and renewables. In particular, Table 3 summarizes the decomposition of word-of-mouth effects: as one may see, renewables are characterized by a high within word-of-mouth, $q_2 = 0.289034$, which is instead almost zero for nuclear power, $q_1 + \delta = 0.048143$. Moreover, nuclear power is affected by a negative cross word-of-mouth, $q_{1c} = -0.238197$, which suggests that the growth of renewables is having a negative impact on nuclear consumption. Conversely, nuclear power had a practically negligible effect on renewables, $q_2 - \delta = 0.002694$. The fact that $\delta = \gamma$ implies a symmetry between the two alternatives for electricity production: what has been lost by nuclear is gained by renewables.

5. Conclusions

The use of competition models allows to evaluate the existence and the relevance of competition/substitution effects in the diffusion of concurring technologies, with benefits on both forecasting and normative considerations. In particular, we have seen that the energy transition in Germany is characterized by a high within word-of-mouth for renewables and a high negative cross word-of-mouth for nuclear, providing a measure for a widespread belief. The substitution of nuclear with renewables is possible because the final product is technically the same: electric energy with conventional specifications. This point justifies the application of the UCRCD models that assume a common residual market potential for the competitors.

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