The German energy transition: modeling competition and substitution between nuclear power and renewable energy technologies

Mariangela Guidolin*, Renato Guseo*

*Department of Statistical Sciences, University of Padua, Italy

Abstract
This paper studies some quantitative aspects of the energy transition in Germany, the Energiewende, which envisages the complete abandonment of nuclear power and a strong reliance on photovoltaic and wind energy for electricity provision. The major aim is to shed light on, and measure with indirect tools, the possible social effects on competition and substitution dynamics characterizing such transition. In doing so, an analysis on the innovation diffusion framework is proposed through 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, in order to test empirically the presence of such substitution effect. The obtained results confirm this conjecture and show that renewables have exerted a significant and measurable effect in determining the observed decline of nuclear power consumption. In particular we find that the diffusion of renewables -wind and solar- is characterized by a high within word-of-mouth, testifying the widespread belief of Germans towards the energy transition, while the parallel diffusion of nuclear power is characterized by a highly negative cross word-of-mouth, due to the competing role exerted by renewables.

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

1. Introduction: the energy transition concept

The expression energy transition indicates a long-term structural change in energy systems. The evolutionary dynamics of primary energy usage have been historically characterized by some major transitions. The field of energy transitions was deeply studied, among others, by the physicist Cesare Marchetti, whose research on this topic, developed at the International Institute for Applied Systems Analysis (Austria), gave a crucial contribution to the understanding of these historical transformations. In his research, (see, for instance, [1], [2], [4]), he highlighted that energy sources are comparable to commercial products competing for a market niche and that the
adoption process of a new energy source may be modelled with a logistic-like function, which is able to describe the learning behaviour underlying it. As highlighted in [2] and [3] the proposal rests on the dominant role of society as a learning system based on the interaction of its agents for specific social and individual aims (survival aims). Complex System analysis or System Dynamics are formal representations of these basic ideas that point to express the role of “Logos”, science and of particular competition/cooperation modeling between alternative species or processes. With specific evidences on the energy context, Marchetti accounted for the historical shifts of primary energy use form sources of wood, coal, oil, natural gas, and nuclear, [5]. As pointed out in [2], historical energy transitions co-evolve with the parallel development of technological innovations, whose diffusion is essential for the growth of a new energy source.

<table>
<thead>
<tr>
<th>Acronyms, nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
</tr>
<tr>
<td>EFR</td>
</tr>
<tr>
<td>EPR</td>
</tr>
<tr>
<td>IAEA</td>
</tr>
<tr>
<td>IEA</td>
</tr>
<tr>
<td>GBM</td>
</tr>
<tr>
<td>NLS</td>
</tr>
<tr>
<td>RETs</td>
</tr>
<tr>
<td>TWh</td>
</tr>
<tr>
<td>UCRCRD</td>
</tr>
</tbody>
</table>

Today, there are important signs that a regime shift is beginning to occur. As noticed by [6], elements of change may be revised in “policies that prioritize greener economies” and “post-Fukushima adjustments in nuclear energy utilization”. The current meaning of energy transition typically indicates a regime shift from fossil fuel and nuclear based systems to renewable energy technologies (RETs), which also implies a shift from centralized to decentralized production of energy with a re–organization of political power and control. In [7] it is observed that energy transitions are characterized by a co-evolution of demand and supply; however the main drivers of historical transformations are energy service demand changes. In other words, it is the demand side of economies that plays a crucial role in the adoption of new energy sources. This appears particularly true in the case of RETs, that imply a sort of democratization of energy through the explicit involvement of citizens, becoming direct producers of electricity. At the same time, institutional commitment by the means of persistent and continuous policies is another key factor for a successful transition in energy systems, [7].

From a technical point of view, five promising RETs are compared, in general terms, in [13]: biomass gasification, molten carbonate fuel cells fed with wood gas, solar photovoltaics, solar thermal and offshore wind in contrast to advanced nuclear technologies, European Presurized Reactor (EPR) and European Fast Reactor (EFR). Comparison is essentially based on qualitative assessments of the relative contribution to climate change and sustainable development. The conclusion deriving from this comparison is in favour of RETs as the new nuclear technologies do not solve well–known critical problems such as, radioactive waste, proliferation risks, and safety issues exacerbated by Fukushima accident. The open question is how a particular nation implements realworld choices over time.

This paper analyzes the regime shift in energy production that is occurring in Germany. Interestingly, the term energy transition was the title of a 1980’s publication of the German Öko-Institut,
which proposed the complete abandonment of nuclear power and oil in favor of renewables. Indeed, the case of Germany has been chosen for its ambitious plan to realize a transition to sustainable energy, through the complete nuclear phase-out and a strong reliance on photovoltaic and wind energy for electricity provision, [8]. This plan, called “Energiewende” (the German expression for energy transition), expects to reach a 35% of electricity production from renewable sources by 2020, and 80% by 2050. In this sense, the Energiewende is considered the world’s most extensive embrace of wind and solar power, [9]. Germany is the largest economy and energy market in Europe, and has the fourth largest GDP in the world, [10]: indeed, with the Energiewende Germany is playing a leading role for the rest of the world since other countries are observing its experience, trying to learn some key lessons and possibly imitate its example. As maintained in [9], Germany is the right country to try the great experiment because “if it fails, it will be bad for Germany, but if it succeeds, the whole world will profit”. According to the definition provided by [11], Germany may be considered a lead market, that is “a market in which the diffusion of a dominant design takes place”, [11]. The development of a design that may become dominant at the international level is typically related to local preferences, environmental conditions and policies, [11]. In fact, one of the most important points arising from the German experience is the ability to drive the transformation through a robust legal and policy framework, [8]. In 2000 the German government promulgated the Renewable Energy Act (EEG), which is the legal tool behind the Energiewende. The EEG favoured an exceptional growth of wind and solar power through the feed-in tariff system, a mechanism that guarantees a minimum purchase price for electricity generated from renewable sources, [12]. As summarized by the Economist in 2012 (see [21]), the Energiewende “was dreamed up in 1980s, became a policy in 2000, and sped up after the Fukushima disaster”. In [12] it is observed that the decision to realize the transition, though recent, originates from three features of German political and cultural history: an environmentally progressive culture, a strong support to RETs through legal tools, a historical reluctance towards nuclear energy.

The case of Germany is studied with regard to the economic effects of renewable energy expansion through a model–based analysis that is grounded on input–output sectoral tools in [14]. The comparison between the expansion scenario (EXP) and an alternative counterfactual scenario with no expansion in renewables has the limits of the conventional definition of the interacting forces. For instance, nuclear power trajectory over time in the Energiewende context does not have a clear definition. However, the main substitution effect in electricity production is dependent on the evolution of these two competitors.

A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies is proposed in [15] and [16]. The proposed simulation is based on a sparse grid optimization that requires specific assumptions on future electric consumptions, high energy–saving retrofit measures in the building sector, cost figures for all components assumed in a stationary market context, which implies a good or mature level of development. This approach does not treat the relevant aspect of substitution between competing technologies and migration from older ones. Moreover, this process requires a social agreement that should be evaluated and measured.

The technical aspects of the current energy scenario in Germany within the goals of the Energiewende programme are analyzed in [17]. Current energy demand, its decomposition, and some foreseen energy demand are examined by identifying their integrability and the involved infrastructural and technological bottlenecks. Among them, the authors mention further developments in wind–power and photovoltaic expansion, biomass conversion technologies, electricity transmission grids, transition duration from fossil fuels to renewables, long–term and short–
term energy storage and related efficiency, conversions of wind and solar energies into syngas. A particular emphasis is devoted to a “non–technical” aspect of the programme: the proposal of the introduction of Exclusively Green Energy Communities (EGEC) in order to stimulate, through demonstration projects, not only technical aspects of real implementations or time table rescheduling, but the social viability of the long–term national venture. In this sense, a quantitative estimation of the substitution effects between nuclear power and renewable technologies is a necessary check base on historical observed data in order to avoid assessments base only on ideal technological scenarios. Technological and social change are two aspects of the same problem. From this perspective, innovation diffusion methodology seems a reasonable framework to understand and forecast the real dynamics of social and economic systems. The technical solution may be only a brick and not a wall.

In [18] it is discussed the admissibility of nuclear fission power as part of sustainable development through an analytic evaluation of 19 criteria organized in five categories concerning: planet, prosperity, risks, people and politics. The analyses highlight that some nuclear power is affordable for present generations when many costs remain unpaid or are not included in a complete life cycle accounting procedure. Developing countries cannot sustain related capital costs and the corresponding technological complexity. The apparent low carbon–free steam generation is attenuated over the entire life cycle that add relevant long–term costs. Renewable energy strategies are contrasted by nuclear power expansion that act as an obstruction and not as a driver of low carbon energy perspective. Conversely, this technology, largely supported by a fossil fuel–driven economy, is hitting the limit of cheap uranium 235. Insurance and re–insurance companies only cover limited aspects of current risks. The best informed actuaries exclude the possibility of a standard risk management with appropriate premium payments and private utilities avoid to have in charge nuclear plants for the increasing costs and risks. The authors suggest the need for a global independent agency to review nuclear power issues with a prominent focus on society’s interests and reveal the collusive positions of “vocal celebrities” and well–known institutions (IAEA, IEA, and UK Department of Energy and Climate Change) that are not super partes.

So what appears important to measure is to what extent the German Energiewende has changed a “conventionally sustainable” old road map pointing to a more realistic perspective based on renewable energy sources. The cumulative demand of different critical minerals towards a high growth scenarios of renewable energy deployment by 2050 is studied in [19]. The authors classify involved technologies for relevance pointing mainly to photovoltaics and wind power and related alternative subclasses based on different materials. Further potential relevant technologies refer to concentrating solar power, electricity storage (lithium ion batteries, vanadium redox flow batteries, electrolisis, etc.) The main result is that German Energiewende may be compatible with the supply of mineral resources suggesting parallel and alternative viable technologies and encouraging increasing resource efficiency and recycling systems for more critical material such as gallium, indium, selenium, neodyminum and dysprosium. This basic confirmation of the solidity of Energiewende strategy must be evaluated in a temporal perspective to verify its operational realization.

In summary, a characterizing aspect of the Energiewende is its primary focus on electricity generation: in fact, one could say that energy transition is an electricity transition, [12]. In analyzing the regime shift from nuclear to RETs, this paper favors an evolutionary perspective and studies simultaneously the historical pattern of consumption of both nuclear power and renewables (namely, wind and solar, put together). Based on BP Statistical Review of World Energy
2014 data, the major aim of this paper is to shed light on, and measure with indirect tools, the possible social effects on competition-substitution process characterizing such transition, establishing the nature of related effects, and the corresponding dynamics. In doing so, an analysis based on the innovation diffusion framework is proposed under the hypothesis that energy sources are similar to products with a finite life cycle. This assumption may appear contradictory in the case of renewables, which, in principle, may determine an open life cycle: however, it may be preferable to consider a limited, even if long, life cycle for currently existing wind and photovoltaic technologies. This does not exclude further more efficient radical innovations in this field in the future and the subsequent identification and estimation with “successive generations” models for instance through Norton and Bass methodologies [20]. Nevertheless, within the current co-existence of alternative technologies, a recent model for competition analysis is employed here, namely the UCRCD (unbalanced competition and regime change diachronic) model by [22], in order to account for the effects deriving from competition-substitution between nuclear and RETs. The proposed results confirm this antagonism and show that renewables exerted a significant and measurable effect in determining the observed decline of nuclear power consumption.

The paper is structured as follows: in Section 2 some key points on innovation diffusion models are summarized. Section 3 presents the models for competition employed, unrestricted and standard UCRCD. Section 4 describes some aspects for model estimation. Based on BP data, Section 5 is devoted to the application to the competing technologies, nuclear power vs RETs, in Germany. Some concluding remarks are contained in Section 6.

2. Background: Innovation diffusion models

Modelling and forecasting the diffusion of an innovation over time in a socioeconomic system is a theme that has attracted 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. Indeed, the diffusion of an innovation is primarily a social phenomenon, whose complexity may be better understood through the contribution of various scientific areas. Traditionally, it has been defined as “the process by which an innovation is communicated through certain channels among the members of a social system”, [23]. As such, innovation diffusion consists of four central elements: innovation, communication channels, time and social system. Its formal representation has historically used epidemic models borrowed form biology, like the logistic equation, in which social contagion represents the driving factor of growth. The logistic equation was formulated for the first time by Verhulst, [24], and was originally used in natural sciences for describing growth processes, like the spread of a disease. In [25] it is noted that the logistic equation represents one of the most powerful technological forecasting tools, almost a “natural law” of innovation diffusion, due to its success in representing dynamics of change in markets and socio-economic systems: the rationale behind the use of this equation in new product domain is that an innovation spreads in a social system through communication like an epidemic disease through the mechanism of contagion between persons. The role of the logistic distribution over time as a natural law has been discussed, from a foundational point of view, in [26], by establishing a direct connection with the catenary function. Typical applications of diffusion models have been life cycles of 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 [27], [28], [29] and [30].
More recently, there has been an increasing interest on the application of diffusion models developed in marketing to the energy sector in order to forecast the evolution of different energy sources, with a growing attention towards renewable energy technologies. A recent review on the theme with special reference to renewables has been provided by [31], highlighting that, unlike other commercial products or technologies, RETs receive significant financial and fiscal incentives. In this sense, renewables differ from other innovative technologies, because their benefits should not be considered just from a financial perspective, but rather from an environmental and energy-security point of view, [32]. Moreover, diffusion rates in the energy domain are very context specific, depending on socio-economic, technological and institutional factors: these aspects may help explain the different speed of diffusion processes in various countries, [32] and [33].

From the modeling point of view, the Bass models, in standard ([34]) and generalized ([35]) versions, still represent an essential reference for the description of univariate processes. The Bass model, BM, describes the life cycle of an innovation, depicting its characterizing phases of launch, growth, maturity and decline. Its purpose is to forecast the development over time of a new product growth, as result of the purchase decisions of a given set of potential adopters. These purchase decisions are assumed to be influenced by two sources of information, an external one, like mass media and advertising and an internal, namely social interactions and word-of-mouth. These sources of information create two distinct groups of adopters: the innovators and the imitators. The formal representation of the BM is a first order differential equation

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

where the variation over time of adoptions, $z'(t)$, is proportional to the residual market, $m - z(t)$, where $m$ is the constant market potential and $z(t)$ are cumulative adoptions at time $t$. Parameter $p$ represents the effect of the external influence, namely institutional communication, and defines the behavior of innovators, while $q$ is the so called coefficient of imitation, an internal effect, and describes the behaviour of imitators, whose influence is modulated over time by the ratio $z(t)/m$ that represents the relative knowledge (or awareness) of the product performances. When diffusion is highly influenced by external interventions able to alter its speed, such as incentive schemes and policies, the Generalized Bass model, GBM, proves particularly useful. The GBM extends the BM by the inclusion of a general intervention function $x(t)$, able to describe several exogenous shocks, modifying the timing of diffusion

$$z'(t) = \left( p + q \frac{z(t)}{m} \right) \left( m - z(t) \right) x(t). \quad (2)$$

Notice that if $x(t) > 1$, we observe an acceleration of the diffusion process, while a delay in adoptions is implied by $x(t) < 1$. When there are no external interventions (i.e., $x(t) = 1$), the GBM reduces to the standard BM. Several applications concerning the adoption of both non-renewable and renewable energy sources have highlighted its central role, see for instance [36], [37], [38], [39], [40].

However, 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. In fact, like any other technological regime, the energy system seems to work under competitive substitution dynamics in an environment with rapidly changing technology and uncertainty, [5]: as pointed out by [7] “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 [41], 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 [43], [44], [45]. Specifically, these models describe a duopolistic competition with sequential market entry. In [43] and [22], changes in the first entrant parameters due to competition are allowed. Moreover, the models proposed in [22], 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, as will be clarified in Section 3.

3. A general model for competition: UCRCD

The general model for competition proposed in [22], the Unbalanced Competition and Regime Change Diachronic Model, 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 \( A \),

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

Notice that, as long as \( t \leq c_2 \) and the second competitor has not yet entered the market, \( z_1'(t) \) 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 \( \delta \) and \( \gamma \) 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 [22], 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.

4. Statistical inference and estimation

The statistical implementation of the models presented in previous section is based on non-linear least squares (NLS), (see [46]), under a convenient stacking of the two submodels; the stacking procedure is necessary in order to obtain a unidimensional nonlinear model directly implemented through Statgraphics, version XVII, with standard nonlinear least squares (NLS) methodology, under Levenberg–Marquardt algorithm. In particular, we have considered the structure of a nonlinear regression model

$$w(t) = \eta(\beta, t) + \varepsilon(t),$$

(4)

where $w(t)$ is the observed response, $\eta(\beta, t)$ is the deterministic component describing instantaneous or cumulative processes, depending on parameter set $\beta$ 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 $R^2$ in the interval $[0; 1]$, namely,

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

(5)

where $R^2_{mi}, i = 1, 2$ is the standard determination index of model $m_i$.

The $R^2$ coefficient has a monotone correspondence with the $F$-ratio, i.e.,

$$F = [R^2(n - v)]/[(1 - R^2)u],$$

(6)

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 independence, identical distribution, and normality, the $F$-ratio statistic, for the null hypothesis of equivalence of the two models, is a central Snedecor’s $F$ with $u$ degrees of freedom for numerator and $n - v$ degrees of freedom for denominator, $F \sim F_{u,v}, [47]$. 

5. Modeling the regime shift from nuclear to RETs in Germany: results and discussion

This section presents 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. These sources of energy have been selected because they are the most relevant 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. These are two major
points of the Energiewende which represents a revolution in the German energy policy, with a substantial change from centralized to distributed generation which implies new financial and social responsibilities.

Here we analyze the annual time series of consumption (in TWh, data source: BP Statistical Review of World Energy 2014, see [48]) 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.

5.1. Results

As one may observe by inspecting Figure 1 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 most general model, the unrestricted UCRCD with $\delta \neq \gamma$ to instantaneous data, whose results are summarized in Table 1.

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 $m_c$. Notice that the estimate $\hat{\delta} = 0.23575$ belongs to the confidence interval of parameter $\gamma$, i.e., $[0.00976, 0.25135]$ and, vice versa, the estimate $\hat{\gamma} = 0.13056$ belongs to the confidence interval of parameter $\delta$, i.e., $[0.10476, 0.36673]$. This simultaneous overlapping may suggest, as a plausible hypothesis, the equivalence of the two parameters, $\delta = \gamma$, that may be statistically tested.

Consequently, for comparison purposes, we estimated the standard UCRCD with $\delta = \gamma$, whose results are summarized in Table 2.
Table 1: Parameter estimates of unrestricted UCRCD model with $\delta \neq \gamma$; ( ) marginal linearized asymptotic 95% confidence limits. Estimates performed on instantaneous data.

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>$p_{1a}$</th>
<th>$q_{1a}$</th>
<th>$m_c$</th>
<th>$q_{1c}$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3302.95</td>
<td>0.00099</td>
<td>0.20089</td>
<td>50632</td>
<td>-0.21492</td>
<td>0.994538</td>
</tr>
<tr>
<td>(2779.2)</td>
<td>(0.00009)</td>
<td>(0.18409)</td>
<td>(236203)</td>
<td>(-0.31456)</td>
<td></td>
</tr>
<tr>
<td>(3826.71)</td>
<td>(0.00188)</td>
<td>(0.21768)</td>
<td>(337467)</td>
<td>(-0.11528)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$q_2$</th>
<th>$\delta$</th>
<th>$p_{1c}$</th>
<th>$p_2$</th>
<th>$\gamma$</th>
<th>D-W</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13636</td>
<td>0.23575</td>
<td>0.00238</td>
<td>-0.00021</td>
<td>0.13056</td>
<td>2.04978</td>
</tr>
<tr>
<td>(0.01639)</td>
<td>(0.10476)</td>
<td>(-0.01096)</td>
<td>(-0.00150)</td>
<td>0.00976</td>
<td></td>
</tr>
<tr>
<td>(0.25633)</td>
<td>(0.36673)</td>
<td>(0.01573)</td>
<td>(-0.00107)</td>
<td>0.25135</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>$p_{1a}$</th>
<th>$q_{1a}$</th>
<th>$m_c$</th>
<th>$q_{1c}$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3302</td>
<td>0.00099</td>
<td>0.20089</td>
<td>10814</td>
<td>-0.23819</td>
<td>0.994059</td>
</tr>
<tr>
<td>(2761)</td>
<td>(0.00006)</td>
<td>(0.18351)</td>
<td>(8867)</td>
<td>(-0.27325)</td>
<td></td>
</tr>
<tr>
<td>(3844)</td>
<td>(0.00191)</td>
<td>(0.21826)</td>
<td>(12760)</td>
<td>(-0.20314)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$q_2$</th>
<th>$\delta$</th>
<th>$p_{1c}$</th>
<th>$p_2$</th>
<th>$\gamma$</th>
<th>D-W</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28903</td>
<td>0.28903</td>
<td>0.00886</td>
<td>-0.00040</td>
<td>-</td>
<td>1.89329</td>
</tr>
<tr>
<td>(0.24503)</td>
<td>(0.24503)</td>
<td>(0.00776)</td>
<td>(-0.00162)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(0.33033)</td>
<td>(0.33139)</td>
<td>(0.00996)</td>
<td>(-0.00080)</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
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. Notice that in this case the confidence intervals of all parameters are very small and with homogeneous sign of the extremes.

In order to evaluate whether the extension implied by the unrestricted UCRCD is significant, we calculated the squared multiple partial correlation coefficient $\tilde{R}^2$ and the corresponding $F$-ratio: in this case, we obtain $\tilde{R}^2 = 0.08$ and $F = 5.47$, which suggests that the assumption $\delta \neq \gamma$ is not really significant, so that the standard UCRCD has been chosen as the best parsimonious modeling option, see Figure 2.

The interpretation of parameters gives very interesting insights on the historical trajectories followed by nuclear and renewables, and on the dynamics of competition and substitution occurring between these alternative technologies. Parameters $m_a$, $p_{1a}$ and $q_{1a}$ refer to the diffusion of nuclear power in the stand-alone phase, that is between 1965 and 1990. We notice that parameter $p_{1a}$ takes a very low value, $p_{1a} = 0.00099$, indicating a very fragile role of the innovative component in the uptake of this energy source. The estimated market potential in the stand-alone phase is $m_a = 3302$ TWh. Interestingly, we may observe that the market potential under competition is notably higher, $m_c = 10814$, which suggests that the entrance in the market of a competitor implies an expansion of the market for all the players. The effects exerted by competition may be inferred by analyzing the word-of-mouth parameters. 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, $q_2 = 0.289034$ that indicates a large social consensus. Conversely, it 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. Also this as-
Table 3: Within product and cross product WOM effects in standard UCRCD model.

<table>
<thead>
<tr>
<th></th>
<th>UCRCD $\delta = \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nuclear RETs</td>
</tr>
<tr>
<td>Within WOM</td>
<td>0.048143 0.289034</td>
</tr>
<tr>
<td></td>
<td>$(q_1 + \delta)$ $(q_2)$</td>
</tr>
<tr>
<td>Cross WOM</td>
<td>-0.238197 0.002694</td>
</tr>
<tr>
<td></td>
<td>$(q_1)$ $(q_2 - \delta)$</td>
</tr>
</tbody>
</table>

pect highlights a systematic change of social consensus in Germany. Conversely, nuclear power had a practically negligible effect on renewables, $q_2 - \delta = 0.002694$. The fact that the equivalence $\delta = \gamma$ is supported by previous test implies a symmetry between the two alternatives for electricity production: what has been lost by nuclear is gained by renewables.

5.2. Discussion

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. From the analysis of the German energy transition with these models, some key results have come out:

1. the diffusion of renewables (wind and solar) is characterized by a high within word-of-mouth, testifying the widespread belief of Germans towards the energy transition;
2. the parallel diffusion of nuclear power is characterized by a highly negative cross word-of-mouth, due to the competing role exerted by RETs.
3. the standard UCRCD model, with $\delta = \gamma$ proves to be the best modeling option. This suggests that, in terms of word-of-mouth effects, what is lost by one competitor is gained by the other
4. UCRCD models assume that the residual market is common to all the involved technologies in the sense that substitution may be complete: this assumption is appropriate in the analyzed case because, as we have previously seen, the German energy transition is focused on electricity production. The direct substitution of nuclear with renewables is possible because the final product is technically the same: electric energy with conventional specifications dispatched through a common power grid.

6. Conclusions

The energy transition occurring in Germany is a regime shift from a fossil-nuclear energy system to a renewable energy one. Interestingly, in [21] this process has been interpreted in light of the concept of resilience, that is “the capacity of a system to absorb disturbance and reorganize while undergoing change, so as to still retain the same function, structure, identity and feedbacks”, [49]. In particular, according to [21], the challenge of the Energiewende may be defined as “transforming the technological structure of the system while ensuring resilient energy provision and social acceptability of the transition process and its side effects”. One critical point is to understand why the Fukushima disaster had a strong impact on German energy policy: in this view, “the Fukushima disaster acted as an exogenous disturbance initiating
the regime shift.” At the same time, the resilience framework highlights the fundamental interaction between sudden shifts and gradual changes: the Fukushima disaster was able to influence German energy policy and accelerate the regime shift because the socio-economic system had long been prepared by programs and policies stimulating the adoption of RETs and the abandonment of nuclear. The proposed analysis in this paper is coherent with the qualitative views expressed in previous scientific research and may provide a further measurable insight on the interplay between the drivers of change: specifically, the study of word-of-mouth effects provides a quantitative measure of the social acceptance towards the regime change. In particular, the negative cross word–of–mouth exerted by RETs on nuclear power is very high and seems to be not reversible as confirmed by the technical analysis based on confidence interval. Conversely, the nuclear power in Germany has a negligible force in contrasting RETs with its specific word-of-mouth as documented by the small positive value of the net effect $q_2 - \delta = 0.002694$.

References