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Forecasting the impact of renewable energies in competition with non-renewable sources

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ABSTRACT

The diffusion dynamics of traditional and clean energy systems, in the energy mix, are studied in a competition modeling, where their interacting life cycles are jointly described. Competition has only been considered recently since diffusion competition models are not easy to be implemented. Data are represented by yearly consumptions (in Mtoe) of traditional sources (coal, oil, gas, and nuclear systems) and a selection of renewable sources (hydroelectric, wind, and solar power) for the US, Europe, China, and India from 1965 to 2014. For each case, we will investigate whether the diffusion level of traditional sources sustains or prevents the spread of renewables and vice versa. For the US and Europe, we will take into account the link between the 2008–2009 financial crisis and the slowdown in consumptions. As a matter of fact, the energy sector is characterized by uncertainty due to the depletion of finite energy sources, the technological and economical problems of renewables, and the hypothesis of shale gas as a possible bridge to renewables that could delay the spread of latter ones. In this scenario, six-year forecasts are provided until 2020.

1. Introduction

By now, it is a matter of fact that the energy mix is slowly changing, but it is still uncertain which direction will be feasible in both the short and long term. Clean technologies have great potential for producing electricity, but their development is slow and depends on several factors, among them incentive schemes and technological problems that need to be overcome. Hydroelectricity often represents an exception among the clean technologies since, in many countries, its exploitation is stable. Non-renewable energies are moving to the last phase of their life cycle, even if it may happen that a new technological innovation can increase the accessibility to a source, at least for a while. For example, fracking has given a new era of gas through shale gas, especially in the United States. The new growing trend of natural gas was unpredictable until a decade ago through national historical data. In fact, new technological discoveries can suddenly change the life cycle of a source. However, even if the life cycle of a particular source is hypothetically extended by a technological discovery, a sensible choice could be waiting before exploiting that direction in order to understand if the new technology can be considered safe. For example, Klein and Whalley [1] encourage caution in considering shale gas as the bridge to renewables since it has negative environmental impacts due to hydraulic fracturing [2–4]. Its effects are worse than the natural gas from conventional sources, its environmental impact (groundwater and surface water contamination and wastewater generation, fugitive methane emissions, and increased seismic activity) has not yet been adequately discussed [3], and its drilling operations have not yet been adequately regulated [5]. Other countries, such as China [6] and India [7,8], are considering shale gas, but these negative effects could change the investments in the energy sector.

Given this uncertainty, the forecasts released in 2013 by the EIA say that world energy consumption will increase by 56% between 2010 and 2040 [9], mostly due to non-OECD countries, and the energy market will expand. In this market, the different energy systems behave as competitors. The entry of new technological innovations may compensate for the exit of technologies for depleted energy sources. At the same time, new technologies may foster the expansion of the market potential size, especially for emerging countries. Usually, it takes time before a new technological innovation arrives to represent a non-negligible market share. This has been the case of green technologies that, for years, have faced difficulty in being adopted due to technological discrepancies with the pre-existing electric system and because they strongly rely on incentive schemes to be economically competitive. Moreover, the competitive effects would also affect the time entry of new technologies and life cycle of pre-existing technologies.

The contribution of statistics here, in the diffusion of an innovation field, is to provide estimates of the market size of each energy system in the future energy mix by extrapolating information from historical data. The best way to deal with this is to use a single complex system in

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order to correctly identify the competition effects [10]. In the past, several attempts were made by analyzing one source at a time, both renewable and non-renewable, in a univariate diffusion framework—for example: oil [11], natural gas [12,13], nuclear energy [14–16], wind power [17,18], biomass energy [19], and photovoltaic system [20,21].

Only recently has competition modeling been considered [22–25,10] since competition is not an easy tool, especially with diffusion models that imply nonlinear estimation. At the moment, competition between two competitors at a time has been considered in the modeling phase.

In the energy sector, the aim of this type of study is to investigate how the diffusion of a technology influences or competes with the diffusion of other technologies. Vestrucci et al. [26] presented the Italian case with competition between firewood and coal, studied in a diffusion framework through a logistic model. Huh and Lee [27] used a diffusion model, taking competition into account through competitors' prices, for the description of renewables in South Korea. Duan et al. [28] used a Lotka–Volterra model to study the evolution of wind and PV solar technologies in leading countries. Guidolin and Guseo [29] analyzed the transition in Germany from nuclear power to renewables (wind and photovoltaic) through an extended Lotka–Volterra model.

In this paper, we attempt to simultaneously analyze all energy sources by focusing on the competition between renewable and non-renewable energy systems. In particular, we consider the total consumptions (in Mtoe) from non-renewable and renewable energies. For non-renewable energies, we refer to coal, oil, gas and nuclear energy (COGN) sources, while for the Renewables, we refer to hydroelectric, wind, and solar power.

As a case study, we will consider the consumptions of the US, Europe, China, and India, which represent four big actors in the world energy trade. From the modeling point of view, since we are dealing with synchronic competition, we will start from the Savin and Terwiesch's model [23]. However, as discussed in Guseo and Mortarino [25], we will further generalize the model in order to estimate totally distinct cross-product competition effects; that is, both the competition effects of the COGN sources on the Renewables and the Renewables on COGN sources have their own parameters. In this way, it is possible for each group of energy systems (that is, the COGN and the Renewables) to isolate the internal contribution of its growth from the external contribution due to the development of the competitor. For cases where the life cycle is not uniform and the diffusion process highlights subsequent waves, we will take this aspect into account to improve the description and increase the forecasts' reliability. As in the model proposed by Guseo and Mortarino [25], parameters would be allowed to change from one wave to the subsequent wave.

We also propose six-year forecasts until 2020 with 3σ predictive bands built under the hypothesis of heteroscedasticity [10]. We focused on short-term forecasts since a wider window may lose meaning in the energy sector now. These years are characterized by high levels of uncertainty in the energy sector due to the depletion of Uranium 235 and other finite sources, the feasibility of shale technology, the technological and economical problems of renewable energies, the increasing demand of electricity in developing countries, and the necessity of reducing CO_2 emissions.

This paper is organized as follows. In Section 2, we briefly present the competition models used. In Section 3, we show and discuss the results of the model fitting to the consumptions of the US, Europe, China, and India. In Section 4, we present concluding remarks.

2. Competition models

Competition exists if there is a market and at least two substitute goods to be sold to potential customers. In the 1960s, the diffusion modeling of a single product started. For this reason, the terminology used comes from the quantitative marketing field, in which the diffusion modeling has the highest number of applications. When a product is launched in the market, the first customers are called innovators since they were informed about the existence of the product by an external source of information such as advertising. However, the product actually takes off when the imitators start to buy it. The imitators are those customers that were informed by internal source such as word-of-mouth (WOM), describing interaction among adopters and non-adopters. Simultaneous to the description of products' diffusion, Rogers [30] introduced the issue of technology diffusion, giving the definition of what can be considered an innovation. In particular, in this paper, we deal with competition among technological innovations: the customers, here, are the final consumers of energy, the sales are represented by consumptions, the product is the energy, the COGN (Coal, Oil, Gas, and Nuclear) sources and Renewables represent the two competing brands in the market, the market potential is the maximum level of consumption achievable in the energy market, and the residual market is the energy consumption that the energy sources can still ensure. Here we assume, for simplicity, a finite potential for both competitors. For COGN, this is reasonable, while for the Renewables, this choice is limited to current technologies that may be expanded in following waves.

Savin and Terwiesch [23] propose a model that splits the interpersonal communication effects due to WOM into (*so*-called) within-brand and cross-brand effects (unbalanced models). The Unbalanced Competition Regime Change Diachronic (UCRCD) model [25] extends the previous model to diachronic competition (two products that enter the market at different launch dates), allowing the parameters of the first entrant to change at the competition's start. Since, in this paper, the competition is synchronic, we will refer to only the competition phase of the UCRCD model, leaving out the stand-alone part of the model where the first competitor stays alone in the market.

Let $z_1(t)$ be the cumulative sales of the first product (i.e., cumulative consumptions of COGN), $z_2(t)$ be the cumulative sales of the second product (i.e., cumulative consumptions of the Renewables), and $z(t) = z_1(t) + z_2(t)$ be the cumulative sales of the category. Let m be the common market potential and $[m - z(t)]$ be the common residual market. Let $z'_1(t)$ be the instantaneous sales of the first product and $z'_2(t)$ be the instantaneous sales of the second product. Then, the expression of the proposed model UUC (Unrestricted Unbalanced Competition) model becomes:

$$\begin{aligned} z'_1(t) &= m\left[p_1 + (q_1+\delta)\frac{z_1(t)}{m} + q_1\frac{z_2(t)}{m}\right]\left[1 - \frac{z(t)}{m}\right] \\ z'_2(t) &= m\left[p_2 + (q_2-\gamma)\frac{z_1(t)}{m} + q_2\frac{z_2(t)}{m}\right]\left[1 - \frac{z(t)}{m}\right] \\ z(t) &= z_1(t) + z_2(t), \end{aligned} \tag{1}$$

The term "unrestricted" comes from Guseo and Mortarino [25], where the constraint $\delta = \gamma$—included both in the model by Savin and Terwiesch [23] and in the UCRCD model—is discussed. Here, the more flexible UUC model, where δ and γ are free, will be used. The development of the first product is characterized by the innovation parameter, p_1, the within-brand imitation coefficient, $(q_1 + \delta)$, and the cross-brand imitation coefficient, q_1. Analogously, the development of the second product is characterized by the innovation parameter p_2, the cross-brand imitation coefficient, $(q_2 - \gamma)$, and the within-brand imitation coefficient, q_2. In this unrestricted version, the within-brand and the cross-brand coefficients become product-specific; that is, δ refers exclusively to the first product and γ to the second product. In particular, δ represents the difference between the within-brand and cross-brand coefficients for the first product, while γ is the difference for the second product: δ and γ are positive if the within-brand effect is stronger than the cross-brand effect, for the corresponding product, and negative in the opposite case, as discussed in Guseo and Mortarino [25].

In the following, we give a few more details to explain how the model interprets the competition dynamic that exists in a market with two products. In the competition regime, the instantaneous sales of a product z'_i, $i = 1, 2$, are the sum of the sales due to innovators and the