Modelling Energy Transition in Germany

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The expression *energy transition* indicates a long-term structural change in energy systems. It is not a new phenomenon: man has made several energy transitions in his short history on Earth. One of the most significant was shifting to an energy system based on fossil fuels (coal, oil, and natural gas) from one essentially based on wood; however, since the 1980s, it has been realized that fossil fuels are at the root of climate change due to carbon emissions into the atmosphere.

Keywords: energy transition ; multivariate diffusion model ; system dynamics

1. Introduction

In short, rapid and deep reductions in greenhouse gas emission are needed to avoid the dangerous effects of climate change and guarantee energy security [1][2]. This transition is often referred to as the decarbonization of the energy sector and aims to shift the system to renewable energy technologies (RETs) by also implying a change from centralized to decentralized energy production. As pointed out in [3], significant reductions can be achieved by using appropriate technologies and policies. Besides a move from fossil fuels to renewable sources, efficiency and savings in the use of energy are seen as complementary viable solutions. In sum, achieving a rapid global decarbonization critically depends on activating contagious and fast-spreading processes of social and technological change within the next few years [4]. According to the International Renewable Energy Agency (IRENA) [5], renewable sources and energy efficiency could potentially reduce carbon emissions from the energy sector by 90%.

With the term *renewable energy*, researchers normally refer to all forms of energy present on the planet, whose availability is renewed indefinitely over time, unlike fossil fuels [6]. Typical renewable sources available today are hydroelectric, wind, and solar energy, but there are also other sources like, e.g., bioenergy generated by the fermentation or combustion of organic mass (such as fertilizer or plants) and geothermal energy, based on heat coming out from Earth's crust (for example, in the form of a geyser) [7].

In the case of hydroelectric, wind, and solar power, the energy released is typically converted into electricity, although only 25% of electricity produced worldwide comes from renewables [6]. Indeed, electrification of the energy system will be necessary to fully exploit the potential of renewables and get the energy transition off the ground [8], and forecasting electricity consumption becomes critical for improving energy management and planning by supporting a large variety of optimization procedures. Today, there are significant signs that a regime shift is beginning to occur in many countries [8]. A specific case, is the regime shift in electricity production in Germany. Indeed, Germany has an ambitious plan to realize a transition to sustainable energy with a strong reliance on photovoltaic and wind power for electricity provision [9]. This plan, called "Energiewende" (the German expression for energy transition), was expected to reach 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 the wind and solar power [10]. The legal tool behind the Energiewende is the Renewable Energy Act (EEG), promulgated by the German government in 2000. The EEG has favored an exceptional growth in wind and solar energy through the system of *feed-in* tariffs [11]. This mechanism guarantees a minimum purchase price of electricity produced from renewable sources. Three characteristics of German political and cultural history have certainly stimulated the transition: a progressive culture of the environment, legal tools to support RETs, and a historical reluctance towards nuclear energy [12]. The technical aspects of the current energy scenario in Germany within the goals of the Energiewende program are analyzed for instance in [13].

The paradigmatic example of energy transition in Germany may be analyzed focusing on the interdependencies between three energy sources for electricity production, namely coal, natural gas and renewables. Specifically, it is interesting to understand whether renewables have a sufficient competitive strength towards fossil fuels.

Figure 1 describes the yearly consumption time series in Exajoule (EJ) of coal and natural gas between 1964 and 2020 and of renewables (wind and solar jointly considered) from 1989 to 2020 (source: BP Statistical Review of World Energy

[14]). As may be easily observed, the time series of coal and gas are simultaneous, while renewables have obviously a more recent history. A possible competitive interplay between these series seems to be captured from the visual inspection of data, but the significance and nature of these effects needs to be tested with a suitable model.

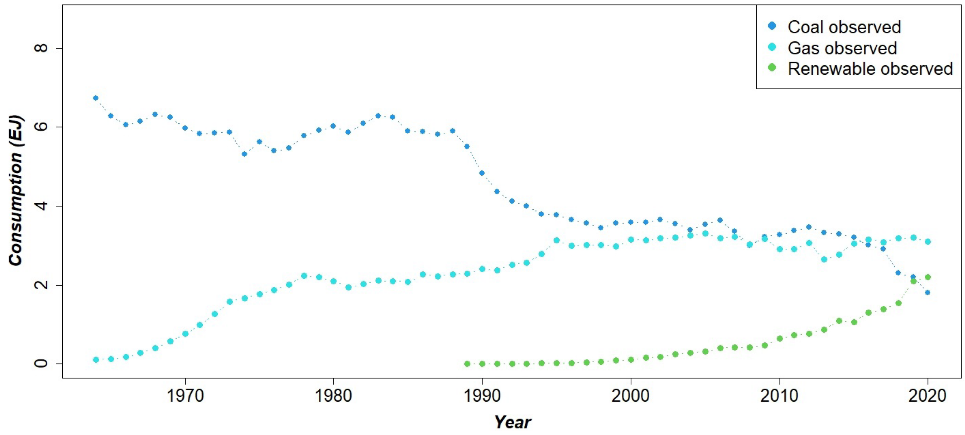

Figure 1. Time series of energy consumption of coal, gas and renewables in Germany (1964–2020).

A well-established stream of research has analyzed the temporal dynamics of energy sources by employing multivariate innovation diffusion models. In one pioneering contribution on the topic [15], Marchetti defined energy sources as comparable to commercial products that compete for a market niche, so it is reasonable to analyze the process of adopting a new energy source through diffusion models. Grubler, in [16], highlighted that energy demand and supply systems co-evolve, with technological innovations mutually enhancing each other.

Within the literature produced in the field, in recent times, several contributions have applied bivariate innovation diffusion models to energy contexts, in order to understand the complex dynamics within energy systems: see for instance [17], where the case of Germany is analyzed with reference to the competitive relationship between nuclear power and RETs, [18], which studies the relationship between non-renewable and renewable energy sources in US, Europe, China and India, [19], focusing on the case of energy transition in Australia by comparing the trends of coal, gas and renewables, and [8], where bivariate innovation diffusion models are employed to investigate the specific role of gas in the electricity transition.

Grounding on this literature, this entry presents an analysis of the case of Germany, by proposing a multivariate innovation diffusion model, which considers the dynamic interplay between coal, gas and renewables. This model, which is based on a system of differential equations, is then represented within the system dynamics approach, through the Stock-Flow Network (SFN) tool. Such complementary description encourages a deeper understanding of the relationships within the energy market. The SFN representation aids understanding the complex feedback process acting in the system and creates a suitable environment for detecting, simulating and evaluating different policy scenarios able to speed up the renewable energy diffusion.

2. Background: Innovation Diffusion Models

2.1. Ordinary Differential Equations Approach

The research carried out on diffusion of innovations originated in the 1960s through the definition of the first models based on ordinary differential equations. Pioneering contributions in this regard are, among others, those of [20][21][22][23][24][25].

The study of diffusion phenomena is a research area that describes and analyzes the growing dynamic of innovations within a social system through a mathematical model [23]. In particular, understanding competition or collaboration dynamics between products or technologies is critical in outlining and describing the trend of diffusion processes [26]. Depending on the situation, the presence of competition can act both as a barrier for the growth of the innovation under consideration and as a stimulus for its development. In the first studies concerning the interactions between several innovations in a single market, researchers used a simplifying assumption to model the time series related to the processes: competition was considered a process in which all the trajectories evolved starting from the same instant in time (*synchronic process*). In [27], the first synchronic model was proposed, which was followed by other works, such as [28][29]. However, in most economic and commercial contexts, products and technologies enter the market at different times. From this consideration, starting from the 2000s, other approaches were developed that consider trajectories starting from different moments in time (*diachronic process*). There are two approaches to analyze competition formalized in *balanced* and *unbalanced* models. Within the balanced models, the same dynamic influences the competitors without distinction. In contrast, [30] were among the first to propose an unbalanced model for competing products by making a distinction to account for different effects within the diffusion of a technology: an internal-influence, which reflects the internal growth dynamics of one technology, and a cross-influence, which identifies the effect of competition exerted by the concurrent technology.

Some important studies that lay the foundations of the methodology used in this work are the balanced model of [31], the mentioned unbalanced model proposed by [30] and the Unbalanced Competition Regime Change Diachronic (UCRCD) model of [32]. Subsequently, the UCRCD model became the basis for some further developments, which include [17][18][19][33][34]. It is important to notice that all the models recalled so far analyze the competition between two products or technologies, while more general models have received a limited attention in literature. To researchers knowledge, there is just one recent article by [35] proposing a diffusion model for three technologies competing in the same market, the 3PM.

2.2. System Dynamics Approach

The system dynamics field came to life between the 1950s and 1960s at the Massachusetts Institute of Technology (MIT) thanks to Forrester [36]. This field has been designed to support studying the structure and dynamics of the systems in which people are immersed and to research the answers inside or outside a system. In particular, the primary objective is the design of policies for continuous improvement and the facilitation of implementations and changes. Drawing from the theory of controls developed in engineering and the modern theory of nonlinear dynamic systems, system dynamics often involves the development of formal models and related simulators to capture complex feedback and create an environment for learning and designing system policies [36].

System dynamics allows building the model representing the system under study, identifying the factors of interest, and researching the cause–effect relationships between the internal or external elements of the system [37]. The systems approach complements other approaches by studying interdependencies, allowing synthesizing insights that have been gained through more disciplinary procedures. An essential characteristic of the systems approach, compared to methods that focus on local and immediate effects, is that circular-causality is considered. System dynamics focuses on how interconnected elements affect each other and, through these other elements, themselves again over time [38], thus capturing aspects that are typically beyond the scope of different approaches. A cause–effect relationship can be defined as positive or negative. It is defined as positive when the two events move in the same direction, or as negative when they move in the opposite direction [36]. Even if it may be relatively easy to identify local relationships between pairs of elements, it is normally difficult to evaluate the effects of interventions on the system, due to unexpected or unwanted consequences, system inertia, and counter-intuitive behaviors. Generally, every action generates a reaction reflected on the action itself as feedback: the decision impacts the environment, which in turn affects the decision [39]. The circular-causality relationships cause this feedback, and complex systems are the result of the interaction of multiple feedback. They can be described and analyzed through a formal representation using the Causal Loop Diagram or the Stock-Flow Network's common languages [40]. The work is inspired by system dynamics analyses that have been applied to electricity generation and energy transition (such as [40][41][42][43][44][45]).

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