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Diffusion of photovoltaic technology in Germany: A sustainable success or an illusion driven by guaranteed feed-in tariffs?

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A B S T R A C T

Germany has served as a role model in photovoltaic technology diffusion amongst house owners in the last two decades. A strong feed-in tariff scheme based on the Renewable Energies Act (EEG) supported - and to some extent - enabled this development, but due to skyrocketing costs it already has been and will be further reduced. So far changes in public policy have only slightly affected house owners with photovoltaic panels on their own house, but future policies have not been decided yet. This article uses the methodology of System Dynamics to develop a model of the German photovoltaic market for small plants on private houses and tests public policies. Amongst them are different scenarios regarding the reduction or even removal of the feed-in tariff scheme in Germany. The results can improve German public policies in the field of photovoltaic technology diffusion and serve as an example for other countries and other renewable energy diffusion cases.

1. Introduction

Fighting climate change has a long tradition in international politics. Already in 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was built to facilitate and jointly address this challenge humankind as a whole face. Numerous studies, conferences and several international agreements followed in the next decades. Amongst them is the Kyoto Protocol, which was ratified 1997 and entered into force in 2005. Each signatory state committed itself to "*implement and/or further elaborate policies and measures in accordance with its national circumstances, such as: (…) development and increased use of, new and renewable forms of energy*" [1]. The recently negotiated Paris Agreement is in line with these goals and highlights the "*increased use of, new and renewable forms of energy (…) and the importance of the engagements of all levels of government and various actors, in accordance with respective national legislations of Parties in addressing climate change*" [2]. This urges especially developed nations to assess new sustainable energy sources and to reduce their greenhouse gas emissions rapidly. Despite some achievements there is still an immense gap to close and every government as well as every individual has to contribute.

Amongst those developed nations Germany has been acting very successfully in the last years [3]. It took a leading role in promoting solar energy as the first country worldwide, which set up a large scale program to promote photovoltaic (PV) panel installations in 1989, the so called '1000 Solar Roof Program' [4]. Results achieved so far are impressive, but not enough: By 2016 around 37% of net energy demand could be satisfied by renewable energy sources, solar power covering around 6.5% in total [5]. By 2050 renewable energies shall account for 80% of total energy supply [6]. By assuming this leading role in solar energy promotion Germany serves as a role model and experiences from the German market have already been and will continue to be transferred to other contexts [7]. The key enabler for this German success story was a strong public policy, especially the feed-in tariff system [3].

Within the German photovoltaic market the share of rooftop PV systems installed by house owners accounts for only 15% of total solar energy production [5], but nevertheless it forms an important pillar of the German solar energy framework in technological and sociological terms. Combined with new storage technologies and the possibility to be directly used by the end customer it can relieve the German energy distribution network [8]. The network is

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currently seen as the bottleneck limiting further growth of renewable energies, as these sources require a more flexible distribution structure than traditional power plants [5,9]. This is mainly owed to the fact, that some renewable energies as wind are limited to a specific geographical area and sometimes show high energy production peaks. In addition, small end-customer PV systems increase visibility of renewable energies and enable the population to participate in the so called ‘energy turnaround’. Since the 1960s there has been a green movement in Germany and the ‘critical mass of interest groups in favor of renewables’ has been an important success factor for solar energy [3].

The legislation targeting renewable energies, namely the Renewable Energy Act (German: Erneuerbare Energien Gesetz (EEG)), has been developed in an iterative process since 2000 [7]. Unexpected problems occurred and so several revisions were necessary. The most recent version of the EEG entered into force in 2017 and introduces a supply-demand-based rewarding system for all photovoltaic plants except from the here considered small end-customer ones [6], substituting the so far applied feed-in tariffs. Future strategies for private households remain unclear and Wirth [5] summarizes this uncertainty in the statement, that the new law both ‘supports and is a barrier to further photovoltaic construction’. Feed-in tariffs have become a burden for private end consumers, as Germany uses a cost redistribution system mainly financed by private end consumers. Moreover it is often criticized that feed-in tariffs do not induce any change in the polluting technologies [4], but just support further growth of renewables. Indeed, until now the growth of small photovoltaic plants in Germany has been impressive, but at this stage both further steep growth or saturation seem likely. In the past feed-in tariffs have driven the growth [4,9], but will it be able to persist without this guaranteed security? The proposed model studies the long-term effect of different ways of removing feed-in tariffs before they will be implemented by another version of the EEG. It contributes to a deepened understanding how the future of photovoltaic energy in Germany could look like and how public policies can achieve a smooth transition.

In order to test the current policies and observe their long-term effects, the system dynamics modeling approach is selected. This methodology meets both the structural characteristics and the aim to achieve a strategic perspective of the public policies.

1.1. System dynamics as a suitable framework

First introduced by Jay Forrester in 1960s at MIT, system dynamics is a simulation modeling technique to analyze complex social systems and offer policy recommendations [10]. The method builds on the endogenous approach to complexity and analyzes problems over time. Feedback loops are major components of the method and represent the fact that decisions of agents influence the decisions of other agents and the system as a whole [11].

In this sense, system dynamics aims to enhance the understanding of complex systems and empower decision makers to select policies, which will lead them to greater success. Thus, the aim of this article and system dynamics are congruent on a meta-level: As previously outlined, our aim is to study long-term effects that occur when applying public policies within the given structure and environment. Strupeit and Palm [9] support this approach by highlighting the importance of getting a broad understanding of the business environment in order to set up a suitable business model, which boosts the diffusion of PV panels. This is exactly what this article aims to achieve: it studies the complex PV market for house owners in Germany with the target to enable decision makers to select the policies and achieve a long-term success to combat climate change.

The system dynamics simulation models use a stock and flow notation. In such models ‘stocks characterize the state of a system and generate the information upon which decisions are based. The decisions then alter the rates of flow, altering the stocks and closing the feedback loops in a system’ [11]. The system dynamics model is then used, to test the system behavior under different assumptions. The selected case of an innovation diffusion is a complex conjunction of relationships between households, already installed plants, government incentives and also mouth-to-mouth advertisement, which finally leads to the number of new installed plants per year [3,4,12]. Considering the time horizon of several decades, the interrelations and feedback loops between the various components cannot been put aside. Moreover, system dynamics has been extensively used in the energy field, with good results, such as for studying energy efficiency [13], electric mobility [14] and PV diffusion [15–18].

Amongst the PV diffusion cases, we highlight the work by Yamaguchi et al. [18], which applied the quantitative formulation of the Bass model to the PV market in Japan. Diffusion is amongst the elementary structures within System Dynamics [11] as well and the use of the Bass diffusion model is recommended in the ‘case of small-scale renewable energy plants diffusion’ [12]. Various authors followed this idea and obtained powerful insights into the PV diffusions studied, for example in Spain [16] and Colombia [17]. As far as the application of system dynamics in German cases is concerned, we have found the case of renewable gas (see Ref. [19]), however, PVs have not been yet studied with a system dynamics approach under the Bass diffusion theory.

1.2. Research design

Following the steps for system dynamics models proposed by Sterman [11], we: i) formulate the model by using the Stock-and-Flow notation and the Bass Diffusion model as the core structure [20]; ii) perform parameter estimation and model calibration; then, iii) we conduct the main model testing procedures, including extreme conditions; afterwards, iv) we introduce the government policies and the formulation of scenarios; our modeling process is completed by v) the evaluation of these scenarios and an outlook on further research topics.

2. Theoretical framework: The Bass diffusion model

The Bass model designed for durable products assumes ‘exponential growth of initial purchases to a peak and then exponential decay’ [20] induced by two major groups of purchasers: innovators and imitators. Innovators are externally influenced, meaning their purchase is driven by advertisement or other external information sources [11]. In contrast imitators are influenced internally, in particular by the number of peers, who have already purchased the innovation [20]. Due to their different purchasing behavior in the beginning of a sales process innovators drive the sales growth whereas later imitators do so until a level of saturation is achieved. The represented pattern is often referred to as a S-curve in System Dynamics' literature.

The basic equation of the Bass model describing the probability of initial purchase at time T is

$$P(T) = p + \frac{q}{m}F(T) \tag{I}$$

where p is the publicity constant, $\frac{q}{m}$ is the constant formed by imitation coefficient q and potential market size m (also referred to as ultimate adopters). The quotient describes adoption by imitation depending on the number of already existing adopters expressed