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Optimal policy identification: Insights from the German electricity market☆

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ABSTRACT

The diffusion of renewable electricity technologies is widely considered as crucial for establishing a sustainable energy system in the future. However, the required transition is unlikely to be achieved by market forces alone. For this reason, many countries implement various policy instruments to support this process, also by re-distributing related costs among all electricity consumers. This paper presents a novel history-friendly agent-based study aiming to explore the efficiency of different mixes of policy instruments by means of a Differential Evolution algorithm. Special emphasis of the model is devoted to the possibility of small scale renewable electricity generation, but also to the storage of this electricity using small scale facilities being actively developed over the last decade. Both combined pose an important instrument for electricity consumers to achieve partial or full autarky from the electricity grid, particularly after accounting for decreasing costs and increasing efficiency of both due to continuous innovation. Among other things, we find that the historical policy mix of Germany introduced too strong and inflexible demand-side instruments (like feed-in tariff) too early, thereby creating strong path-dependency for future policy makers and reducing their ability to react to technological but also economic shocks without further increases of the budget.

1. Introduction

'there must be a "sweet spot" in […] subsidy design space at which subsidies are maximally effective in triggering adoption and wide-spread diffusion without wasting money on adopters who would have adopted anyway' (Cantono and Silverberg, 2009, p. 495)

The diffusion of renewable electricity technologies (RET) is widely seen as a crucial part for establishing a sustainable energy system in the future. However, the current energy system is designed for and locked into the usage of fossil fuels (Unruh, 2000), so that the required transition is unlikely to be achieved by market forces alone. For this reason, many countries have recently implemented different policy instruments to support innovation in and diffusion of RET (Johnstone et al., 2010; Rodrik, 2014). Most instruments try to foster an innovative activity in RET by lowering R & D costs for private companies or by performing R & D in public research institutes (del Río and Bleda, 2012); or directly support their diffusion via subsidies. The main goal of these policies is to make RET competitive (in terms of costs) with fossil fuels inside the electricity grid.[1]

In this diffusion-oriented context, two specific features of RET gain importance, namely the possibility of small scale electricity generation without the need of further inputs and intermittent (unstable) nature of its production, which have been so far largely ignored in the modeling studies (Kverndokk and Rosendahl, 2007; Fischer and Newell, 2008; Kalkuhl et al., 2012). Combined with storage, these features can be used by electricity consumers to become electricity producers themselves (partial autarky) or even to achieve full autarky from the electricity grid: ability to generate and store as much or even more electricity than required in a normal period (Luthander et al., 2015). This becomes particularly important as with the decreasing costs and increasing efficiency of storage and RET the necessary investments required to

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[1] Further rationales for the implemented instruments include (but not limited to) mitigation of market failures (e.g., knowledge spillovers offering richer opportunities for economic growth) and strategic policy objectives such as security of energy supply (Fischer et al., 2012; Lehmann and Gawel, 2013).

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become fully autarkic from the electricity grid fall. The latter can be considered as an unintended side effect of the original policy measures and is a paradigm change in the electricity generation systems of developed countries, which were built around large, fossil electricity generating plants that distributed an electricity through complex grids.[2]

Another incentive to install RET and storage comes from re-distribution of costs of the electricity generated from more expansive renewable sources to cheaper fossil fuels (e.g., Hoppmann et al., 2014), which raises the consumption price one has to pay for electricity from the grid. By becoming electricity producers themselves, consumers avoid the extra costs and hedge against rising prices in the future. Once more consumers become fully autarkic, the costs for consumers remaining in the grid increase, creating the possibility of a snowball effect. This puts the stability of the grid in question, forcing the policy makers either to change their policy or risk a collapse of the grid.

This study aims to identify an optimal mix of policy instruments stimulating diffusion of RET and preserving stability of the electricity grid.[3] Since the transition is an out-of-equilibrium-process (Farmer et al., 2015), we utilize evolutionary modeling approach (Safarzynska et al., 2012) and build a novel agent-based model (ABM). We find it better fitting our research question in comparison to more traditional techniques (like DSGE models) because we avoid presuming unrealistic cognitive capabilities of our agents (De Grauwe, 2011), given the uncertainty related to constantly changing prices of fossil and RET but also unforeseeable stochastic events (e.g., emergence of the small scale storage technology). As it will be clear from Section 2, actors facing uncertainty act differently compared to perfect foresight: either leaving the market under low demand (fossil electricity producers) or installing RET plants if no RET available on the market (consumers). Furthermore, we aim to address income inequality and interaction among heterogeneous agents, which would have been incompatible with the traditional representative agent assumption (Farmer et al., 2015; Safarzynska and van den Bergh, 2017). The latter is particularly important since, as we demonstrate in this paper, the same policy instruments differently affect consumers stimulating some of them to install RET plants and sell electricity to other consumers, thus, fundamentally changing the electricity market, demonstrating emerging properties out of individual decisions (Battiston et al., 2016) and causing an (infrastructural) system failure (Jacobsson and Bergek, 2011).[4] In the last years, ABMs have become popular to model transitory processes (see, e.g., Nannen and van den Bergh, 2010 and Safarzynska and van den Bergh, 2013) and electricity markets (see, e.g., Sensfußet al., 2007, Weidlich and Veit, 2008, Guerci et al., 2010 or Ringler et al., 2016 for a recent overview on smart electricity grids). In addition, there is a large body of literature utilizing this approach to investigate the problem of diffusion of eco-innovations (see Cantono and Silverberg, 2009, Bleda and Valente, 2009 and Windrum et al., 2009).

This manuscript has two main objectives. The first one is to illustrate in a history-friendly manner (see Malerba et al., 2008; Garavaglia, 2010), which policy instruments played a critical role in the electricity market of Germany in the early 1990s in fostering transition towards the use of RET. Back then, a low number of large fossil power plants supplied the whole economy with electricity, which was transmitted via the electricity grid. From this situation onwards we show that policy intervention was necessary to start the transition and is still necessary if the transition shall progress further.

Second, to investigate which possible mix of instruments (allocation of the fixed budget across available instruments) is likely to deliver the best outcomes (in terms of diffusion reached and grid stability preserved) in the near future.[5] We purposely underline importance of grid stability, as intermittent electricity supply has several adverse effects. The most obvious is the risk of blackouts, which hinder production, displease people and damage electrical devices (see e.g. Liu et al. (2011) or Farhoodnea et al. (2013)).[6]

The rest of the paper is organized as follows. In Section 2 we present the basic model together with a description of policy interventions applied in Germany. In Section 3 we address the parameter calibration issues of our model, compare its evolution over the 'history-friendly' period with empirical findings and stress stylized facts observed. Section 4 presents a counter-factual analysis, where we identify optimal policy mixes for different time periods. Section 5 discusses the implications of the present study and concludes.

2. The model

This section presents a model meant to serve a consistent but concise representation of routines, relationships and behaviour of economic agents as indicated in available literature. We try to balance between following appreciative theorizing making our model empirically oriented and implementing mechanisms closely reconstructing some real world processes (such as merit-order pricing), but keeping our model simple and well-suited for logical explorations helping to understand what factors make the model behave as it does.[7]

Two connected markets, the one for electricity and the one for electricity generation equipment, are modeled (Fig. 1). These markets are populated with three different types of actors, namely electricity consumers, fossil electricity producer and equipment manufacturers. Two technologies for electricity generation are available, fossil fuels and RET. The heterogeneity inside both technologies (i.e., nuclear, coal and gas for fossil on the one hand, and wind and solar energy on the other hand) as well as possible emergence of sub-technologies (e.g., mono- versus polycrystalline photovoltaic) is ignored deliberately to reduce complexity while loosing little additional insight. Note that under RET we solely understand those new technologies that have been experiencing an immense rise in the last two decades providing renewable but intermittent energy supply. For that reason, we concentrate on wind and photovoltaic leaving hydro-power and biomass outside the scope of RET, assuming the latter two being a part of the fossil (stable and established) technology.[8]

The model is run for T periods (months), where T has a maximum of 360. For the first twenty years we apply policy interventions in a history-friendly manner as it was done in Germany in 1990–2010 (described in detail in Section 3). For the last ten years, we aim to identify an optimal mix of policy interventions to reach 26% diffusion of RET by 2020 – policy target formulated by German Federal Government (2010).[9] In addition, we compare different policy mixes

[2] For details on the visionary perspective of the future electricity market see Rifkin (2011).

[3] In the literature there is no universal definition of circumstances, under which grid may break down, and for simplicity we penalize the percentage of unstably produced electricity over time.

[4] For the same reason, we avoid existing stylized models of technology diffusion such as epidemic or probit models (see Cantono and Silverberg (2009, p. 488) for an overview), but unpack the consumer decision (and resulting technology adoption) (see Section 2.4 for details).

[5] Alternatively, the model could be easily adjusted to compromise along the third dimension (budget), but then one must declare how to weight cost and benefit of the policy (we leave it for future research).

[6] In reality intermittent nature of RET forces the state to maintain a fleet of backup power plants and conduct a costly adjustment of the power generation from fossil plants. Due to the recent refuse from nuclear power, the hazard of (short) blackouts in Germany has even increased.

[7] The entire code related to the model is written in R (version 3.1.1), which is a free software, and will be available as electronic appendix of the paper.

[8] Hydro-power has long been applied for electricity generation, indicating that the best locations are already in use, limiting the possibility to increase electricity generation from it. Biomass, on the other hand, is limited by the availability of soil to grow the plants needed, which conflicts with the needs to feed an ever increasing human population.

[9] Since the biomass and hydro-power technologies are not considered in the scope of RET and also can hardly increase their share in the electricity market (in 2010 it was around 8.9%) in the next decade, we assume that the photovoltaic and wind technologies alone have to contribute in reaching the target of 35% set by German Government, i.e. increase their share from the current 8.1% to 26%.