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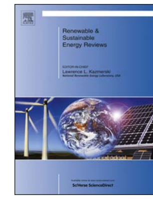

Difficulty is critical: The importance of social factors in modeling diffusion of green products and practices

Katarzyna Byrka [a,*], Arkadiusz Jędrzejewski [b], Katarzyna Sznajd-Weron [c], Rafał Weron [b]

[a] *SWPS University of Social Sciences and Humanities, Faculty in Wrocław, Poland*
[b] *Department of Operations Research, Wrocław University of Technology, Poland*
[c] *Department of Theoretical Physics, Wrocław University of Technology, Poland*

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ABSTRACT

Despite the very positive – as measured by market surveys – attitude towards eco-innovations and sustainability in general, the actual market penetration of green products and practices generally falls behind the expectations. In this paper we argue that considering *difficulty of engagement*, as used in the Campbell Paradigm, is of critical importance when modeling diffusion of eco-innovations. Such a notion of difficulty possesses three desired properties: (i) parsimony – it is represented by a single value, (ii) interpretability – it can be regarded as an estimator of the otherwise complex notion of *behavioral cost*, and (iii) applicability – it can be easily measured through market surveys. In an extensive simulation and analytical study involving empirically measured difficulty and an agent-based model spanned on different social network structures, we show that innovation adoption may exhibit abrupt changes in market penetration as a result of even small changes in difficulty. The latter may be of particular interest to policy makers who have to make strategic decisions when introducing socially – but not necessarily individually – desired products and practices, like dynamic or green electricity tariffs.

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* Corresponding author.
E-mail addresses: kbyrka@swps.edu.pl (K. Byrka), arekjd@gmail.com (A. Jędrzejewski), katarzyna.weron@pwr.edu.pl (K. Sznajd-Weron), rafal.weron@pwr.edu.pl (R. Weron).

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1. Introduction

In response to climate change, low-carbon policies have been recently enforced worldwide. However, effective transition to green energy depends not only on efforts of policy makers, but also on consumers' acceptance of novel products or ideas [1–6]. Similarly, technological progress in energy distribution alone does not guarantee sustainable consumption patterns [7,8]. In extreme cases it may even lead to phenomena such as the *rebound effect* [9,10], i.e. an increased consumption of energy following an improvement in the technical efficiency of appliances or delivered services.

Survey research shows that most customers hold positive attitudes towards various types of eco-innovations. At the same time, adoption rates of solutions such as dynamic electricity tariffs remain unsatisfactorily low [11–13] and social movements arise to challenge proposals to develop renewable energy installations, such as onshore wind farms [14]. The NIMBY or 'Not In My Back Yard' concept is often used to describe what at first seems to be a confusing *intention-behavior gap* between high levels of public support for eco-innovations and frequent non-engagement or even local hostility towards specific project proposals [1,15–17]. The empirically observed discrepancies yield the need to identify factors that affect adoption rates [18–20]. And as Gyamfi et al. [21] argue, social psychology and economic behavior models should be used to overcome these challenges.

A well explored factor that fosters diffusion of green products and practices is conformity to others [22]. Innovations such as dynamic electricity tariffs naturally involve uncertainty triggered by insufficient knowledge. In such situations of uncertainty, opinions and behaviors of friends and neighbors often serve people as a guideline for their own behaviors [23–25]. Accordingly, in empirical research *peer effects* were found to increase adoption of solar panels [26] or reduce residential energy usage at households [17,27,28]. Conformity has been also considered in innovation diffusion models, in particular in the context of adoption of dynamic electricity tariffs [20], sustainable consumption and heating patterns [29,30], electric vehicles and sustainable transport [31–33], wood-pellet heating [34,35], stationary fuel cells [36] or residential photovoltaic systems [37–39].

A somewhat less studied factor, but potentially equally relevant, is the cost related to adoption that may effectively hinder this process [40–42]. If external barriers are modeled in the literature at all, they usually refer to price regulations and economic burden set on customers [20,29,34,43]. We argue, however, that adoption of sustainable products and practices bears costs that go well beyond financial expenses. For example, turning on one's washing machine after midnight to benefit from lower prices of electricity requires rescheduling of daily chores and vigilance at night time. Ignoring external barriers and arising costs in modeling behaviors may result in unreliable analyses and forecasts.

To address these issues we develop a novel agent-based model (ABM) of eco-innovation diffusion. Apart from considering social influence (i.e. conformity to neighbors or peers and agent independence), we introduce costs defined as difficulty of adopting a given behavior. We demonstrate that difficulty is not an abstract construct but can be measured empirically in a relatively straightforward way. Using survey data from the Netherlands and Poland, we show how the differences in difficulty can be interpreted as barriers set on sustainable behaviors in cross-country comparisons.

The remainder of the paper is structured as follows. In Section 2 we review the eco-innovation diffusion literature and discuss the most important features of a good ABM for modeling the diffusion of green products and practices. Next, in Section 3 we introduce the notion of *difficulty of engagement*, as used in the Campbell Paradigm, and argue that it possesses three desired properties: (i) parsimony – it is represented by a single value, (ii) interpretability – it can be regarded as an estimator of the otherwise complex notion of *behavioral cost*, and (iii) applicability – it can be easily measured through market surveys. In Section 4 we show how difficulty can be efficiently implemented in an ABM of eco-innovation diffusion. First, in Section 4.1 we briefly describe the Monte Carlo modeling framework, then in Section 4.2 we provide analytical calculations for complete graphs (i.e. fully connected networks of agents). In Section 5 we present and discuss the obtained results. Finally, in Section 6 we wrap up the results and discuss policy implications.

2. What makes a good eco-innovation diffusion model?

Modeling of innovation diffusion has attracted academic interest since the seminal works of Fourt and Woodlock [44], Rogers [45] and Bass [46] in 1960s. Particularly the Bass model, which is defined by a simple differential equation that characterizes the diffusion as a contagious process initiated by mass media and propelled by word-of-mouth communication, has triggered numerous studies in the literature; for reviews see [47,48]. In the context of eco-innovations, variants of the Bass model have been used among other to study the diffusion of wind power technology [49], green electricity tariffs [19], stationary fuel cells [36], household energy efficiency technologies [50], photovoltaic-system support schemes [51,52] and consumer demand for smart metering tariffs [53].

The downside of aggregate innovation diffusion models, such as the Bass model, is that they possess very limited predictive and explanatory power. They are not designed for analyzing what-if scenarios, they do not explicitly consider consumer heterogeneity nor the complex dynamics and interpersonal relationships encountered in real-world social systems. On the other hand, ABMs provide the required flexibility and over the last two decades have become a widely used approach in the innovation diffusion literature [48] and the social sciences in general [54–56].

In their recent review on agent-based modeling and simulation in electricity markets, Ringler et al. [57] classify ABMs as a subset of multi-agent systems. The focus of their paper is eventually on reviewing ABMs for analyzing *decentralized structures and market integration*, in particular the aspects of smart electricity grids. However, they do acknowledge that the agent-based approach is also used to model the functioning of *competitive wholesale markets*, provide *agent-based decision support tools* and study *electricity prosumer behavior*. Our paper can be classified as belonging to the latter class, despite the fact that we do not explicitly consider electricity prosumers (i.e. entities that are both generators and consumers), rather generic consumers of various eco-innovations.

It is not easy to define what makes a good model for the diffusion of green products and practices. There are many approaches, even within agent-based modeling itself [48,56,58]. Like for any model design, simplicity and reality (or usefulness) are the key factors. However, as Jager and Mosler [59] nicely put it, the challenge resides in simplifying the often complex theories of social science and the complex reality into simple sets of rules. In this Section we discuss the most important – in our opinion – features of a good ABM for modeling diffusion of eco-innovations and comment on how they can be implemented. Before we move on, we would like to emphasize that (i) although focused on diffusion of sustainable products and practices, in some aspects the following discussion reaches far beyond this modeling context and that (ii) all models – no matter how good – are only simplistic representations of reality and should not be used in a mechanical way for the conduct of policy, definitely not without allowing for judgmental adjustment.