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Finite Element Method for forecasting the diffusion of photovoltaic systems: Why and how?

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HIGHLIGHTS

- The paper reviews the scope of using FEM in social science phenomena.
- Also, it applies FEM to a semi-hypothetical case study of spatial heterogeneity.
- The case is the diffusion ratio of solar PV systems in a given region over time.
- The paper presents why and how FEM can be used to forecast the diffusion of solar PV systems.

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ABSTRACT

The Finite Element Method (FEM) has been used in the broad field of continuum mechanics in engineering disciplines for several decades. However, recently, some scholars have attempted to apply the method to social science phenomena. What is the scope of using FEM in social science-related fields? Anchored in the literature on social sciences, this paper, firstly, reviews the scope of using FEM in social science phenomena, and then applies FEM to a semi-hypothetical case study on the diffusion of solar photovoltaic systems in southern Germany. By doing so, the paper aims to shed light on why and how the Finite Element Method can be used to forecast the diffusion of solar photovoltaic systems in time and space. Unlike conventional models used in diffusion literature, the computational model considers spatial heterogeneity. The model is based on a partial differential equation that describes the diffusion ratio of photovoltaic systems in a given region over time. The results of the application show that the FEM constitutes a powerful tool by which to study the diffusion of an innovation as a simultaneous space-time process.

1. Introduction

Photovoltaic (PV) systems, solar energy systems that generate electricity from solar radiation, are vital in achieving the transition toward sustainable energy production. In 2013, the global cumulative installed capacity of PV systems increased 35% in comparison to the year before, albeit with a slowdown in European countries [1].[1] The diffusion patterns of ecological innovations such as PV systems are hard to forecast. The diffusion patterns of such innovations vary not only from country to country [4] but also from a spatial region to another (see e.g., [5,6]). To what extent can we model the diffusion of ecological innovations when spatial heterogeneity exists? It is a hard task not only for ecological innovations, but also for any kind of innovations in general (see [7,8]).

The literature on the diffusion of innovations has focused on modeling methods for decades. The early studies on this phenomenon described diffusion as a one-dimensional, time-dependent *S*-curve (see [9]), investigating the factors influencing the diffusion through regression analysis [10,11]. Several studies have provided a variety of differential equations formulating such one-dimensional *S*-curves (e.g., [12–15]). Other studies have introduced two-dimensional models, considering both time and space [16–18]. However, the two-dimensional models brought computational complexity and had been rarely applied for a long time. With the emergence of agent-based models in 1990s and increasing computational capacity, some recent studies attempted to tackle

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[1] By the end of 2013, the global cumulative installed capacity reached 136.7 GW. This accounts for 0.7% in the global share for electricity production [2]. However, it should be noted that, in some regions, an increase in cumulative installed capacity does not necessarily mean an increase of cumulative number of installations (see [3]).

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both the space and time dimensions on modeling diffusion of innovations, addressing the spatial heterogeneity in social systems (e.g., [19–22]).

Unlike the conventional models of PV systems' diffusion (e.g., [23–26]), the spatial dimension has recently been considered in some studies on the diffusion of PV systems (e.g., [27,28]). These studies have used a downscaled unit of analysis at the local or regional level rather than the national level. Although this approach explained the differences of one-dimensional diffusion paths at different locations, it still lacked an explanation of the effects of spatial heterogeneity on two-dimensional diffusion paths, i.e., how innovations propagate in a spatiotemporal domain that has heterogonous variables.

The Finite Element Method (FEM) is one means by which to model the effects of spatial heterogeneity on the diffusion of innovations. FEM is a numerical tool for approximating the solutions of large-scale problems that are based on partial differential equations. It reduces the spatiotemporal continuum problem, which consists of an infinite number of unknowns, to one with a finite number of unknowns [29]. It originated from the need for solving complex elasticity and structural analysis problems in engineering sciences in 1960s. The model has since been extended and applied to the broad field of continuum mechanics in the engineering disciplines (such as civil, aeronautical, biomechanical, chemical and automotive) [30]. For example, it is often used in energy-related engineering problems such as forecasting the heating and cooling demand of a residential building [31,32] and the design and modeling of the thermoelectric modules [33,34]. However, recently, the model has been borrowed by a number of studies on social phenomena as well (e.g., [35–37]).

Anchored in FEM, this study attempts to offer three main contributions to the literature. Firstly, it presents the scope of using FEM in social science-related fields such as, among others, the research stream on the diffusion of innovations. Secondly, it sheds light on why and how FEM can be used to model the effects of spatial heterogeneity on the diffusion of innovations. Thirdly, it applies FEM to a semi-hypothetical case study on the diffusion of solar photovoltaic systems in southern Germany.

The rest of the paper is organized as follows. Section 2 explains the theoretical background on the diffusion of innovations and presents a literature review on the scope of using FEM in the social sciences. Section 3 describes the formulation of a mathematical model and the semi-hypothetical case study used in this study. Section 4 presents results and discussions. Finally, Section 5 is devoted to conclusions, presenting the limitations for future research.

2. Theoretical background and literature review

2.1. Spatial heterogeneity in diffusion of innovations

Innovations are diffused among the members of a social system over time [38]. A spatial dimension is also of crucial importance to understand such process [16]. Not all members of a social system are equally influenced or by each other, i.e., spatial heterogeneity [39]. Externalities and market infrastructures that support diffusion are spatial as well [16,40]. Several empirical studies have shown that innovations can be adopted by particular countries, cities, or local communities earlier than the others, e.g., wind energy by Denmark [4], PV systems by southern Germany [6] and Facebook by Ivy League universities [41]. Consequently, as studied previously [16,18], wavelike diffusion patterns may occur due to spatial heterogeneity. Fig. 1 presents such wavelike diffusion curves in respect to location, e.g., country, region, city or local community.

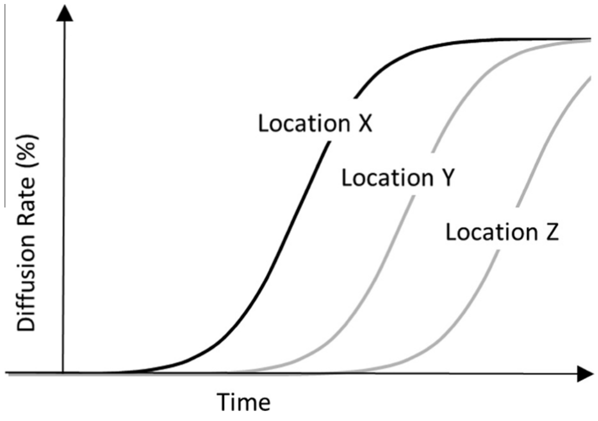

Fig. 1. Wavelike diffusion patterns of a particular innovation.

The wavelike diffusion patterns may occur from a variety of reasons, including spatial heterogeneity. Some particular countries, cities, local communities or individuals can adopt an innovation earlier than others, e.g., due to the higher innovativeness [38] or spatial proximity to an innovation source [18]. Consequently, the high reputation and demonstration effect in such early adopting locations may result in wider adoption by other individuals in other regions (see e.g., [42]). This phenomenon resembles wave propagation or heat transfer in natural sciences. Innovations, as waves and heat do, may propagate from one or multiple sources to other locations in space. Inspired by such resemblance, several researchers have attempted to model innovation diffusion in a spatiotemporal domain by borrowing equations from wave propagation (e.g., [43]) and heat transfer (e.g., [17]).

2.2. Modeling diffusion of PV systems

The diffusion of PV systems has been modeled from various theoretical perspectives through a variety of methods. The study of Mesak and Coleman [26] appears as one of the first contributions of this particular research field. The authors extended the model of Bass [44] in order to forecast the PV systems' diffusion for the residential sector in Kuwait. Their study addressed the link between government subsidies and the PV systems' diffusion. Assuming that the diffusion of PV systems is based on price evolution, Luque [24] combined the learning curve approach [45] with a demand elasticity model. As a result, he forecasted both the market and price evolution of PV systems. The learning curve approach was also used by Masini and Frankl [25]. They simulated the diffusion of PV systems in five southern Europe countries under different scenarios. Watanabe and Asgari [46] attempted to link the dynamic behavior of a learning coefficient with that of innovation diffusion. They developed a mathematical formulation of the logistic growth function which incorporates innovation diffusion and its carrying capacity. The model was applied to the Japanese case of PV systems from 1986 to 2000.

Kobos et al. [47] extended the debate by combining the frameworks of learning by doing and learning by searching. Based on the estimation of the cost curves and learning elasticity through regression analysis, they examined the experience curve analysis of wind energy and PV systems under several scenarios. Based on the well-known Bass model [44] and the extension of it [48], Guidolin and Mortarino [23] forecasted the diffusion patterns of PV systems in several countries. Their paper showed the important differences among several countries, presenting the different stages of the diffusion process. However, the comparison between