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Original research article

Consumer preferences and the influence of networks in electric vehicle diffusion: An agent-based microsimulation in Ireland

Daire McCoy[a,b,*], Seán Lyons[a,b]

[a] The Economic and Social Research Institute, Dublin, Ireland
[b] Department of Economics, Trinity College, Dublin, Ireland

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ABSTRACT

We implement an agent-based, threshold model of innovation diffusion to simulate the adoption of electric vehicles among Irish households. We use detailed survey microdata to develop a nationally representative, heterogeneous agent population. We then calibrate our agent population to reflect the aggregate socioeconomic characteristics of a number of geographic areas of interest. Our data allow us to create agents with socioeconomic characteristics and environmental preferences. Agents are placed within social networks through which the diffusion process propagates. We find that even if overall adoption is relatively low, mild peer effects could result in large clusters of adopters forming in certain areas. This may put pressure on electricity distribution networks in these areas.

1. Introduction

Previous articles in this journal have examined diffusion of new electricity technologies, from exploring the motivations of early adopters of solar electricity in the United States [1], to using stated preference methodology to study the diffusion of photovoltaic generation and electric vehicles in Japan [2]. We complement this research by taking a more computational approach in modelling the diffusion of electric vehicles amongst Irish households.

Pasqualetti et al. highlight the important interplay between energy, geography and society [3], this is an important element of our research and we include a spatial dimension, in which our model is applied to geographic areas of interest.

Electric vehicles (EVs) have been around since the mid-nineteenth century but have only recently been offered as a mass-market alternative to private cars with petrol and diesel engines. They are considered an important element in decarbonising the transport sector and a number of governments have introduced initiatives to encourage their adoption. While this may have environmental benefits, both in direct emission reductions and in helping achieve CO_2 reduction targets in electricity generation [4], negative externalities also exist with mass-adoption. A large engineering literature documents the negative effects clustering of electrical load and uncontrolled charging of large numbers of EVs could have on low-voltage distribution networks [5–7]. At the aggregate network level, high penetrations of these vehicles, when charging, may exacerbate existing peaks in electricity demand [8]. Even if overall adoption levels are very low, this could be concentrated in relatively few areas, due to the heterogeneous spatial distribution of individuals. This effect could be exacerbated if there is spatial dependence in adoption behaviour.[1]

To examine this problem we create a tool to simulate how adoption patterns and clustering might develop over time and across space. Adoption is modelled as a binary choice. Agents have a threshold beyond which the benefits to adoption exceed the costs. Their utility is a function of their socioeconomic characteristics, environmental behaviour and attitudes. Their utility from adoption increases as their peers adopt and as the innovation gains popularity within the population. Agents are heterogeneous, drawn from a detailed, nationally representative study connected to an Irish electricity smart-metering trial. Agent populations are spatially explicit; we can generate populations of agents to match any geographic area of interest.

* Corresponding author at: The Economic and Social Research Institute, Whitaker Square, Sir John Rogerson's Quay, Dublin 2, Ireland. Tel.: +353 1863 2006; fax: +353 1863 2100.
E-mail address: daire.mccoy@esri.ie (D. McCoy).

[1] This has been shown to occur in the adoption of solar PV panels in California [9], High-voltage air conditioning systems in Chicago [10]. Also in the adoption of hybrid electric vehicles [11] and [12].

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In determining the overall diffusion level in the population, we find that network type matters and that it is important who adopts first. When our analysis is applied to populations representative of certain geographic areas we find that even mild peer effects can generate high adoption and clustering in these areas even if the overall level is quite low.

While our analysis is applied to Irish data, the literature above illustrates that this is an international problem. This methodology could easily be applied to other products and countries, provided there is adequate spatially linked census data that can be combined with a suitable micro-level dataset. Furthermore, evidence exists that the structure of social networks can remain quite consistent over time and across different countries [13,14]. Given this, the results from this research could be of benefit to researchers and policymakers in other countries.

2. Agent-based models

Agent-based modelling or ABM is a form of "bottom-up" modelling with its roots in Complex Adaptive Systems [15]. This field is chiefly concerned with the study of how seemingly complex systems can arise from the interactions of relatively simple components. It is informed by a diverse range of disciplines, initially from sciences such as ecology, physics, computer science and applied mathematics. More recently this methodology has been embraced by economists and sociologists.[2]

This type of modelling is useful when describing systems of interacting agents, that exhibit emergent properties not easily deduced by aggregating the preferences of individual agents. Macal and North [15] consider an ABM to be a computer model in which the objects are self-contained, autonomous entities that interact with each other within an environment. The behaviour of an agent is based on "*the current state of its interactions with other agents and the environment*." An agent will have rules that define its behaviour and within more sophisticated models an agent may be able to adapt its behaviour and learn from its experiences.

While not strictly an ABM, an early model of social influence and a demonstration of how simple rules can produce complexity was Schelling's model of population segregation in US cities [18]. By using a very simple Markov process to describe each individual's behaviour, the model could produce results that mimicked real segregation patterns remarkably accurately. Another interesting aspect of this was how the emergent dynamics of the system at equilibrium can be vastly different from the individual preferences; "*there is no simple correspondence of individual incentive to collective results*". In a related example [19], Granovetter demonstrated how slight perturbations to initial distribution of preferences can lead to vastly different outcomes in populations that on aggregate appear very similar. Thus underlying the inherent problem with the use of aggregate models that do not consider interactions. While Granovetter was concerned with the decision to join a riot and Schelling with segregation patterns, similar techniques can also be used to describe the dissemination of new ideas and the adoption of new technologies.

ABMs have been widely used to study the diffusion of new technology. We will mainly focus on the diffusion of "green" technologies, with a particular interest in threshold models for the purposes of this work.

2.1. Agent-based adoption models

Within an ABM framework, the diffusion process can take different forms. Linder [20] uses a Bass diffusion model to simulate adoption profiles for EVs amongst households in Stuttgart in 2020. Based on microdata they construct different adopter types and simulate various scenarios of spatial diffusion. They find that adopters will concentrate in urban areas and that spatial differences will become quite apparent by 2020.

Tran [21] explicitly models social network effects to examine their interaction with individual preferences in innovation diffusion. The author simulates adoption profiles for a variety of competing vehicle types; including petrol, diesel, EV and hybrid electric vehicle (HEV). Using heterogeneous agents, it is found that network influence can be an important factor in driving high levels of adoption, even if agents have low individual incentives to adopt. However, he cautions that homophily can account for a lot of what first appears to be contagion. Other work by the same author [22], examines the techno-behavioural aspects of diffusion.

Threshold models are also widely used throughout the literature. Eppstein et al. [23] develop spatially explicit, agent-based consumer choice models of plug-in hybrid electric vehicle (PHEV) adoption to assess the market's sensitivity to various input parameters, such as fuel prices, battery range, purchase price and government subsidies. Agents have characteristics such as age and salary. Social groups are modelled as homophilous networks with fat-tailed degree distributions. An agent's threshold is defined as the proportion of adopters within its social group required for the agent to adopt; this is negatively correlated to their salary – the authors argue that wealthier agents would be less risk averse, thus having a lower threshold.

Hamilton et al. [24] model technology diffusion when consumers are uncertain about the performance of a new technology versus the old one. The agent environment is a square lattice of N cells and agents receive electricity from three potential sources; the grid, solar or CHP. Agent's thresholds are normally distributed and heterogeneous. An interesting aspect of this paper is the emergence of "*punctuated equilibria*". This is a characteristic of a complex system, in which negligible changes in inputs can induce dramatic shifts in system outputs. This feature is observed empirically when the diffusion process does not follow the textbook S-curve.

Other research simulates the adoption of smart-metering technology [25]. This paper has similar features to others mentioned in that agents have local and random interactions on a grid, allowing for networks which exhibit small-world and scale-free properties. An interesting feature of this paper is the finding that a random and dispersed initial seeding can yield a much higher overall diffusion rate than a controlled centralised one. This has interesting policy implications when one considers government interventions to induce adoption of socially beneficial technologies.

A big problem inhibiting the widespread adoption of green technologies is consumer indifference. This is explicitly modelled by Kowalska-Pyzalska et al. [26], in which the authors examine the diffusion of dynamic electricity tariffs. Again, the environment is modelled as a square lattice. Influence is channelled through nearest-neighbours and media. Indifference is essentially noise in the system and can arise if the product offers both advantages and disadvantages between which the agent is unable to compare. They find that due to high levels of indifference, widespread adoption will be "virtually impossible" in modern societies, highlighting the need for better information in order to overcome this.

The focus of our research broadly follows a number of other papers in which agents have a utility function associated with the adoption of a new product. Agents have a threshold beyond which the benefits of adoption exceed the costs and they adopt. Within

[2] Miller and Page [16] provide a very useful introduction and a recent paper by Sornette [17] provides an excellent historical summary of cross-pollination between financial economics and physics.