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Diffusion of solar photovoltaic systems and electric vehicles among Dutch consumers: Implications for the energy transition

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ABSTRACT

A key issue in smart grid visions is the integration of the energy and mobility systems. Electric vehicles (EVs) can be charged with renewable photovoltaic (PV) solar power, and contribute to the integration of solar power in the electricity network via vehicle-to-grid systems. In such systems the role of consumers becomes crucial as they both generate and store energy. We investigate differences between PV and EV adopter groups and the implications of these differences for the transition to smart energy systems. We study how socio-demographic characteristics of the consumer base influence regional diffusion patterns. In turn, we build scenarios to explore the influence of diffusion patterns on the viability of regional EV-PV integration in terms of energy use and regional self-consumption. The results point out large differences in the spatial diffusion patterns between EV and PV. These differences have implications for the transition to smart sustainable grids; vehicle-to-grid systems may not be viable for certain regions.

1. Introduction

Visions of a sustainable future couple the widespread diffusion of electric vehicles to energy supply from renewable sources [1]. In these visions, electric vehicles (EVs) act both as a source of demand [2] and a storage option for excess renewable energy in vehicle-to-grid (V2G) systems [3]. The adoption and use of renewable energy technologies and electric vehicles by consumers will determine the characteristics of the future electricity grid. Independent micro-grids are a likely outcome when the same consumers adopt both technologies [4]. But if the two technologies appeal to different groups of consumers in different regions, national (super-) grids may be needed to interconnect local grids [4,5].

Understanding these interactions requires a co-adoption perspective [6], as well as taking into account consumer heterogeneity and spatial diffusion patterns. We study the early market development of different clean energy technologies to gain insights in which solutions for integrating these technologies in the existing infrastructure are viable and what their potential contribution to a future more sustainable energy and mobility system is.

More specifically, in this paper, we compare and link the adoption of photovoltaic (PV) solar power and electric vehicles (EVs) by using unique micro-level diffusion data. As a case study we focus on the Netherlands. Our empirical work consists of two parts. First, we analyse the recent diffusion of PV and EV in the Netherlands, and characterize the adopters of these technologies, by linking diffusion data to neighbourhood characteristics via a regression model. This provides insights in the potential for co-adoption and a profile of the early adopters. Using the Bass model of diffusion [7], we estimate future diffusion of PV and EV for different regions of the Netherlands. We use PV self-consumption as a central concept to link these two technologies. PV self-consumption refers to how much electrical energy is consumed by the loads supplied by the local PV solar panels [8]. Higher levels of PV self-consumption will result in decreased stress on the electricity grid and therefore easier integration of PV solar panels in the existing infrastructure. Several countries including China, Japan and Italy have policies in place to increase PV self-consumption of households [9]. PV self-consumption can be increased by energy storage and demand side management (DSM) [9]. EVs can contribute to load balancing via smart charging and V2G [10]. Combining adopter profiles with scenario analysis enables us to investigate the viability of V2G systems and come to policy recommendations.

Our study offers a new approach for taking users into account in energy systems modelling, using a variety of modelling techniques. Hereby, we quantitatively demonstrate the large impact users have on the viability of the EV-PV combination in a future energy system. Our model estimates the viability of V2G systems for different energy scenarios and contributes to the larger effort of integrating insights from social sciences with energy science [11–13]. The remainder of the paper is structured as follows. Section 2 discusses the background of our

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study, Section 3 our methodology and Section 4 the results. In Section 5 we discuss the main contributions, limitations and policy implications of our study and Section 6 concludes the paper.

2. Background

The European Union has the ambition to increase adoption levels of both PV solar panels and EVs. Recently, the European Parliament has voted to ensure that by 2030, half of electricity demand should be produced by wind, solar and biomass [14]. Furthermore, the European Commission has put forward legislative measures that should support energy consumers to become prosumers with PV solar panels [15]. EVs are regarded as having the potential benefits of reduced oil consumption and reduced emissions of CO_2 and other pollutants [16]. The European Commission supports a European wide electromobility initiative called Green eMotion[1], aiming to facilitate EV market roll-out.

In the Netherlands, PV and EV adoption sharply increased in recent years. In 2016, installed PV capacity rose to 2.1 GWp [17]. In 2015, the Netherlands ranked 4th in installed PV capacity and 9th in cumulative installed PV capacity for the EU-28 [18]. The number of registered battery electric vehicles (BEVs) increased by 40% to 13,105 in 2016, and the number of registered plug-in hybrid EVs (PHEVs) increased by 27% to 98,903 [19]. In 2015, 9.7% of newly registered cars were EVs, and the Netherlands had the most EV sales within the EU [20]. Both technologies have large potential for growth, since less than 6% of household rooftops have solar panels, in total providing less than 1% of total annual electricity production, and BEVs and PHEVs combined amount to less than 2% of the total car fleet in the Netherlands. The broadly supported National Action Plan on PV power states a target of 10 GWp in 2023 [21]. The Dutch government has the ambition that by 2030 all new vehicles sold in the Netherlands are zero-emission vehicles [22].

There is both a daily and seasonal mismatch between household electricity demand and PV production. Most PV power is produced around midday, when demand is low. Demand is high in the winter and low in the summer, as the Netherlands has cool summers and moderate winters. To address the imbalance between PV power supply and household demand several Dutch on-going projects aim at developing smart charging of EVs and V2G [23]. Combined with being a front-runner in EV deployment, this makes the Netherlands a good case for studying the integration of PV and EV.

The uptake of new technologies usually follows an S-curved pattern where diffusion is initially slow, followed by a take-off phase of fast diffusion before the diffusion levels off and the market is saturated. Rogers [24] explains this S-curve from social processes where different groups, with different socio-demographic characteristics, decide to adopt the innovation at different points in time, starting with adoption by innovators followed by early adopters, early majority, late majority and laggards. Following Rogers' classification, the diffusion of PV is in the early adoption stage and the diffusion of EV is in the innovator stage in the Netherlands. Insight in the characteristics of innovators and early adopters is pivotal as these are key groups in the diffusion process and shape the early market.

There is a growing body of literature focussing on the drivers and barriers of both PV adoption and EV adoption. In the case of PV adoption, studies have focussed on the role of costs [25–30], environmental attitudes [25], policy incentives [31,32], business models [33–35], and peer effects [36–39]. Several studies on PV diffusion identify socio-demographic factors drive unique diffusion patterns [25,39–47]. Factors consistently found to have a positive effect on PV adoption are the proportion of middle-aged residents [25,39,41] and education level [39,41,43]. Interestingly, the effect of income differs among these studies, with some studies finding a positive effect [30,40,41,47] and others finding a negative effect [28,39,44,46]. Other factors found to have an influence are political preferences [41,47], ethnicity [41], lifestyle [43], housing density [38,40,41], and house ownership [25,42]. Research on factors affecting EV adoption has mostly focused on the role of costs, charging infrastructure and individual factors such as range anxiety, emotions, attitude towards the environment and symbolic attributes of EVs [48–50]. Furthermore, several studies stress the influence of socio-demographic factors on EV diffusion [51–54]. A notable difference between these studies and studies on PV adoption mentioned earlier [39–43] is that in studies on EV adoption the socio-demographic factors are usually discussed as input for a diffusion model and not the key focus of the research. Factors found to have an effect on EV adoption are income [51–53], size of the local car fleet [52], education level [51], family composition [51,54], and political preferences [55].

The scientific literature on the influence of socio-demographic factors on PV and EV diffusion patterns allows for indirect comparison of PV and EV adopter groups. In this study we directly compare the socio-demographic characteristics of EV and PV adopters on a neighbourhood level to get insight in the general profiles of both EV and PV adopters.

We complement these profiles with estimations of future diffusion of PV and EV to investigate its impact on the energy system and come to overall conclusions and policy recommendations. Several approaches to diffusion forecast modelling exist, with varying aspects of focus and levels of refinement [56,57]. Models used for forecasting PV diffusion include the Bass model [31,58,59], which has its roots in the diffusion of innovation theory formulated by Rogers [24] and agent based models (ABMs) [43,60,61]. ABMs are a popular tool for forecasting EV [53,54,62–68]. Other studies base their forecasts on methods using s-curves, such as the Fisher-Pry model [52], pearl curves [69], and the Bass model [70]. In the latter study, the Bass model is combined with discrete choice models and system dynamics. S-curve approaches such as the Bass model offer less flexibility than ABMs, since these are basically an extrapolation of current trends. S-curves are often used as forecasting tools rather than as tools to perform ex-ante policy evaluation. One of the major advantages of ABMs is that such models offer a flexible environment allowing the inclusion of a wide variety of factors such as social networks, subsidy schemes, and information campaigns, while at the same time enabling the use of theoretical models such as the Bass model. A main application of agent-based diffusion models is ex-ante comparison of policies aimed at stimulating diffusion.

We use the Bass model of diffusion to estimate the future diffusion of both technologies. The Bass model of diffusion uses Rogers' classification of adopters; innovators can decide to adopt an innovation at any point time, while the timing of adoption for all other groups depends on the decisions of other members in the social system. In this epidemic model of diffusion, adoption patterns are ultimately determined by the spread of information amongst consumers. The Bass model is well suited for application on micro-level diffusion data as available in the present study, and has been applied before for both PV diffusion [31,58,59] and EV diffusion [70], as well as for analysing differences in diffusion among regions within a country [71]. We prefer to use the Bass model over other formulations of s-curves since, in contrast to for instance the Fisher-Pry model, its parameters can be directly linked to concepts from innovation diffusion theory, such as the spread of information and heterogeneous consumer groups.

3. Methods

This section discusses our data sources and methodology. Our methodology consists of two parts. First, we link PV and EV adoption levels to neighbourhood characteristics via a regression model. This will allow us to contrast and compare the adopter groups for these technologies, using country level data. Second, we investigate the implications of the differences between these adopter groups by estimating future diffusion of PV and EV via the Bass model of diffusion, and link these estimates to the energy systems. Section 3.1 presents our data sources, Section 3.2 presents our method for the regression analysis and Section 3.3 introduces the Bass model of diffusion. Finally, we present our method to link the diffusion of PV and EV to the energy system in Section 3.4.

[1] See http://www.greenemotion-project.eu/ for program website.