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Towards smart grids: Identifying the risks that arise from the integration of energy and transport supply chains ☆

Jan Willem Eising [a,*], Tom van Onna [a], Floortje Alkemade [b]

[a] Liander N.V., Utrechtseweg 68, 6812 AH Arnhem, The Netherlands
[b] Utrecht University, Copernicus Institute of Sustainable Development, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

HIGHLIGHTS

- Grid capacity problems due to EV integration expected in 2015 in urban areas.
- A GIS-based simulation assesses risks associated with large scale EV integration.
- Risks are assessed on neighbourhood level using GIS data.
- Grid operators can use our method to improve investment planning.

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ABSTRACT

This paper identifies the risks for the functionality and reliability of the grid that arise from the integration of the transport and supply chain. The electrification of transport is a promising option for the transition to a low carbon energy and transport system. But on the short term, the electrification of transport also creates risks. More specifically, when promising technological such as vehicle-to-grid and smart-grids are not yet available on a large scale, the rapid diffusion of electric vehicles and the recharging behaviour of consumers can create risks for grid functioning. In order to assess these risks, this paper present a GIS-based simulation method that assesses electricity demand and supply on the neighbourhood level. The paper combines local level electric vehicle diffusion forecasts, with neighbourhood level data about the grid additional capacity. Application of the model to the Netherlands shows that risks for grid functioning already appear as early as 2015. More specifically, the diffusion of electric vehicles is found to compromise the functioning of the grid on the short term in densely populated areas such as Amsterdam. In these neighbourhoods early and fast adoption of electric vehicles coincides with the presence of an older grid with less additional capacity. The model provides insights for grid operators as well as for policy makers that seek to stimulate the transition to sustainable energy and transport systems, and can be used as a strategic tool to plan (smart) grid investments.

1. Introduction

The electrification of transport is widely considered a promising option for the transition to a low carbon energy and transport system. The envisioned benefits are largest when the deployment of electric vehicles is combined with the deployment of renewable and other low-carbon energy technologies such as solar panels and wind turbines [1,2]. This low-carbon transition requires an integration of the energy and transport supply chains. In the new integrated supply chain the energy grid changes from a one-way hierarchical grid to a two-way, more interactive (smart) grid with distributed renewable energy as a source of supply and electric vehicles as a (flexible) source of demand as well as a storage option.

Such smart grid solutions are also necessary to ensure grid functioning when a large number of electric vehicles will be connected to the existing grid. While several earlier studies assume that the diffusion of electric vehicles will be slow enough for capacity planning to respond adequately, and that vehicle charging will coincide with the supply of energy from renewable sources or take place during off-peak hours [3,4], the diffusion of EV is outpacing the implementation of smart grid technology in many countries and concerns about grid functioning are increasing [5–8]. For

* Corresponding author. Tel.: +31 629454179.
E-mail address: janwillem.eising@alliander.com (J.W. Eising).

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example in the Netherlands, the diffusion of electric vehicles is rapidly growing,[1] supported by ambitious policy scenarios [9,10], while recharging data shows that the early adopters mostly recharge their electric vehicles during times of existing peak demand.[2] More research is needed on the possibilities to influence the recharging behaviour of electric vehicle adopters, but on the short term the effect of electric vehicle diffusion could thus be a substantial increase in peak demand. On the middle- and long-term, smart grid solutions are a promising option to mitigate these effects. However, grid failures in the early days of electric vehicle diffusion might also negatively affect user acceptance and thereby the diffusion of these technologies on the long term [11]. Identifying the risks that arise from the integration of the energy and transport system is necessary in order to plan the location and timing of grid investments and the implementation of smart grid technologies and thereby ensuring grid reliability on the long term.

Current country-level scenarios for the diffusion of electric vehicles may underestimate these risks for grid reliability as they do not take into account local heterogeneity. More specifically, the local diffusion of electric vehicles is characterised by large differences between geographical areas and this heterogeneity on the local level is expected to increase in the future [12–14]. The expected additional energy demand from electric vehicles as predicted in the national scenarios is thus unevenly distributed, with areas of very high as well as areas with low increases in additional energy demand. This heterogeneity could amplify the risks for the functioning and reliability of the grid. Moreover, the load-availability of the grid is also characterised by an unbalanced geographical distribution. As a consequence, the risks for grid functioning and reliability are expected to be higher and more imminent when neighbourhoods with lower grid additional capacity are facing a faster local diffusion of electric vehicles than the national-scale scenarios [6].

In order to assess these risks, the impact of the diffusion of electric vehicles needs to be assessed on a smaller scale than in the current studies [3,7,14]. This paper therefore combines local level diffusion forecasts (estimated from current local diffusion and neighbourhood characteristics), with local level GIS data about the grid additional capacity in order to identify the energy security risks that arise during the transition of the transport system. We thereby extend earlier studies of the local diffusion of electric vehicles [15] by also taking into account supply side characteristics, and earlier stylized simulation models [16–20] by integrating GIS based data in our simulation. We present our method using a unique dataset provided by Dutch grid operator Liander. Liander is the largest grid operator of the Netherlands, supplying electricity to 37% of the households in the Netherlands through over 40,000 medium voltage/low voltage transformer (MV/LV) substations. We base our simulation on current data about EV diffusion and energy demand, for two reasons. First, this conservative scenario gives us an accurate description of short term risks. Second, the outcomes of the simulations will provide guidance to the relative advantages of the local implementation of smart grid technologies and infrastructure investments, and to the relative disadvantages of local diffusion of fast-charging stations. In summary, the proposed method will help grid operators to better plan the location and timing of (smart) investments in order to mitigate the risks associated with the diffusion of electric vehicles.

The remainder of the paper is organised as follows. Section 2 provides a brief introduction to the diffusion of infrastructure dependent technologies. Sections 3 and 4 presents the data and the methods used. Section 5 presents the results of the simulation. Section 6 concludes and discusses the presented results and method.

2. The diffusion of infrastructure dependent technologies

Innovation diffusion processes often follow an *S*-shaped pattern as described by Fisher and Pry (FP) [21]. The FP model predicts the diffusion of a technology using the following model:

$$f = 1/2(1 + \tanh\alpha(t - t_h)) \tag{1}$$

where α is half the annual fractional growth in the early years of diffusion, t_h is the time at which the diffusion has reached 50% and f is the fraction of the potential market that is substituted by the new technology. Grübler [22] has applied the FP model to the diffusion of infrastructure dependent technologies, such as vehicles. Using empirical data, he showed that the diffusion of a successful new technology and its infrastructure are interdependent and follow a similar *S*-shaped curve of diffusion, but that the diffusion of infrastructure often precedes the of the technology. Insights in the diffusion patterns of EV may thus also provide insights regarding the desired patterns of (smart grid) infrastructure investments.

The cumulative adoption curve as modelled by FP is the outcome of the aggregation of the individual adoption decisions of consumers. As consumers are heterogeneous, the exact shape of the curve may vary considerably according to geographical area. In his work on individual adoption processes Rogers [23] has identified five consecutive adopter categories, ranked by innovativeness: innovators, early adopters, early majority, late majority and laggards. He thereby models innovation as a social process where earlier adopters influence later adopters. Rogers has empirically identified the following group sizes for the different adopter categories: 2.5% innovators, 13.5% early adopters, 34% early majority, 34% late majority and 16% laggards. Generally the innovators and the early adopters, the first consumers that adopt a technology, are characterised by a higher income and a higher social status [23]. This was also found to be true for the early adopters of electric vehicles [15].

One of the mechanisms through which early adopters of an innovation influence the adoption decision of later adopters is through the increased observability of the innovation [23]; consumers are more likely to adopt a technology they can actually observe in their environment. Spatial remoteness between consumers, as in sparsely populated rural areas, decreases the observability of a technology and thereby negatively influences the adoption decision of a consumer [24]. Urbanisation, in contrast, has a positive influence on the adoption decision of a consumer, as was also observed for the diffusion of plug-in electric vehicles [15]. An additional factor is that for clean fuel cars in general, and for electric vehicles in particular, adoption is more likely if the household already owns another vehicle [25,26]. In addition, Schuitema et al. [25] suggest that the refuelling range of a vehicle, a considerable disadvantage of current electric vehicles, is of less important when buying a second car compared to a first car.

3. Data

3.1. Infrastructure

Electric vehicles are charged using charging stations. In the Netherlands the early diffusion of electric vehicles was stimulated as initially most models were sold including a complementary private charging station or a free public charging station. These

[1] NL Agency [Internet]. Cijfers Elektrisch Vervoer. Ministry of Economic Affairs. [update 2013 May 14; cited 2013 June 10] available from: <http://www.agentschapnl.nl/onderwerp/cijfers-elektrisch-rijden>. Dutch.

[2] E-laad [Internet]. Opladen elektrische auto's zorgt voor piekbelastingen [update 2013 May 16; cited 2013 June 10] Available from: <http://www.e-laad.nl/submenunieuws/424-opladen-elektrische-autos-zorgt-voor-piekbelastingen>. Dutch.