Transportation Research Part D 47 (2016) 336–356

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Market dynamics and indirect network effects in electric vehicle diffusion

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ARTICLE INFO

Article history:

Keywords:
Two-sided market
Indirect network effects
Product diffusion
Electric vehicles
EV charging services

ABSTRACT

The diffusion of electric vehicles (EVs) is studied in a two-sided market framework consisting of EVs on the one side and EV charging stations (EVCSs) on the other. A sequential game is introduced as a model for the interactions between an EVCS investor and EV consumers. A consumer chooses to purchase an EV or a conventional gasoline alternative based on the upfront costs of purchase, the future operating costs, and the availability of charging stations. The investor, on the other hand, maximizes his profit by deciding whether to build charging facilities at a set of potential EVCS sites or to defer his investments.

The solution of the sequential game characterizes the EV-EVCS market equilibrium. The market solution is compared with that of a social planner who invests in EVCSs with the goal of maximizing the social welfare. It is shown that the market solution underinvests EVCSs, leading to slower EV diffusion. The effects of subsidies for EV purchase and EVCSs are also considered.

1. Introduction

The electrification of the transportation sector through the diffusion of plug-in electric vehicles (EVs), coupled with cleaner electricity generation, is considered a promising pathway to reduce air pollution from on-road vehicles and to strengthen energy security. However, the diffusion of electric vehicles in the United States has had mixed results so far. Annual new EV sales increased nearly 7-fold from about 18,000 in 2011 to 116,100 in 2015. Yet, the market share of EVs was only about 0.73% in the new vehicle market by 2014 (Hybridcars, 2014).

A similar trend exists in the deployment of public charging services. The U.S. has built about 9900 charging stations with about 26,000 charging outlets (U.S. Department of Energy, 2015), due in part to the direct and indirect investments of federal and local governments. For example, the Department of Energy (DoE) provided 230 million dollars from 2013 to establish 13,000 charging stations (Electric Transportation Engineering Corporation, 2013). It has been hoped that such investments will stimulate the EV market, driving its market share toward long-term growth and stability.

The growth trends of EVs and EVCSs have strong temporal and geographic couplings as shown in Fig. 1. This is the "cluster" phenomenon of alternative fuel vehicles discussed in (Winebrake and Farrell, 1997), which is the first article to discuss the network effects between the alternative fuel vehicles and the fueling infrastructure. Consumers' EV adoption in the EV market is affected by the availability of EV charging stations whereas the level of EVCS investment strongly

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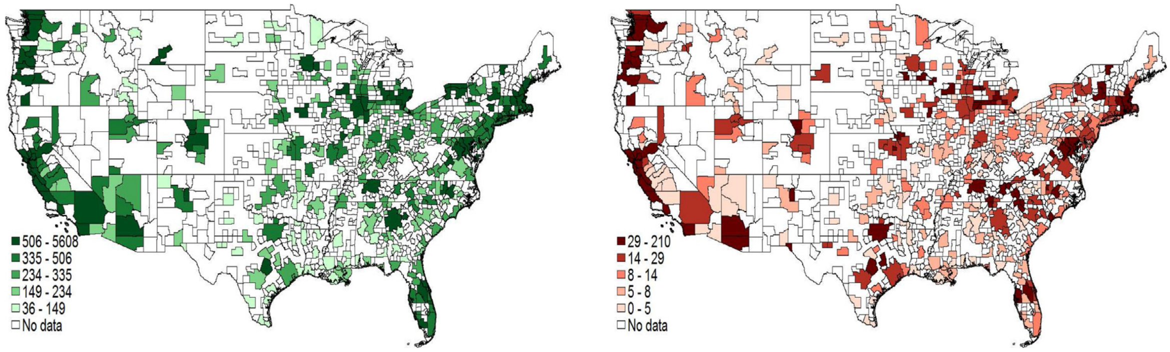
http://dx.doi.org/10.1016/j.trd.2016.06.010
1361-9209/



(a) EVstock per million people. (b) Public charging stations per million people.

Fig. 1. EVs and public charging stations in Metropolitan Statistical Areas in 2014 (Hybridcars, 2014).

depends on the size of EV stock. Thus areas with a lower cost to adopt charging stations will attract more EVs and more EVs incentivize the investors to build more charging stations.

The reason behind the growth of the EV market, or the lack of it, is multifaceted. The growth is driven partially by the increasing awareness of the environmental impacts of gasoline vehicles, superior designs and performance of some EVs, and, by no small measure, subsidies in the form of tax credits provided by the federal and state governments. However, the EV industry faces stiff skepticism due to the high purchase cost of EVs, the limited driving range, the long charging time, and the lack of public charging facilities.

The manufacturer's suggested retail price (MSRP) of the 2016 Nissan Leaf, Ford Focus Electric, and Chevrolet Volt are $34,200, $29,170, and $25,670, respectively, which are more than $10,000 above the purchase price of comparable gasoline vehicles, such as Nissan Sentra, Ford Focus, and Chevrolet Cruze. To make EVs equally attractive as internal-combustion vehicles, federal and state governments provide a tax credit subsidy up to $7500 for each purchase of EVs. Meanwhile, the cost of electric vehicle batteries, which is the major cost of electric vehicles, has been reduced by more than 65% since 2010. It is projected that, by 2020, EVs will become more economic than internal-combustion vehicles even without government subsidies (Bloomberg New Energy Finance, 2016). Besides the quick drop of the battery cost, the low operation cost of EVs also significantly offsets the high capital cost (Electric Power Research Institute, 2013).

The limited driving range of EVs, however, restricts the adoption significantly. By 2016, Nissan Leaf has an range of 107 miles after a full charge, comparing with the range of 99 miles of Ford Focus Electric and 53 electric miles of Chevrolet Volt. While the gasoline vehicles can easily achieve a driving range of over 400 miles per tank of gas. The anxiety of running out of electricity makes the EV charging infrastructure and charging time important considerations when consumers choose vehicles.

There are typically three levels of charging rate, among which Level 1 is used as residential charging choice, and Level 2 and DC fast charge (DCFC) are usually used as public charging stations.[1] The use of higher level charging rate will dramatically reduce the charging time. But the building cost of high level charging stations are also significantly higher.

Level 1 provides charging from a standard residential 120 V AC outlet. Overnight charging can replenish about 40 miles of driving range. However, a completely depleted battery could take up to 20–22 h to completely recharge. Level 2 uses 240 V residential or 208 V commercial AC power, which will supply up to approximately 15 miles of travel for one hour of charging to vehicles with a 3.3 kW onboard charger, or 30 miles of travel for one hour of charging for vehicles with a 6.6 kW onboard charger. To fully charge an EV, it would take around 7 h. Level 2 equipment needs a dedicated electrical circuit to improve safety thus requires professional electrical installation. The cost of installing a single port in a residential house is a little bit more than $1000, over half of which is the hardware cost (Josh Agenbroad and Ben Holland, 2014). The cost of installing a level 2 charging station in public stations, which is the dominant charging rate nowadays, varies from $2000 to $15,000 with the number of ports, station features and brands. DC fast charging requires commercial grade 480 V AC power circuite so it is only available in public charging stations. DCFC transforms the AC power to DC and supplies up to 40 miles of range of driving for every 10 min of charging, or fully recharge in 30 min. The cost of a DC charging station is between $50,000 and $100,000 due to the expensive hardware and the frequent need to install a 480 V transformer. When traveling long distance using EVs, public charging stations are necessary to reduce the anxiety of the lack of electricity. Comparing to the gasoline vehicles, the charging time of EVs is significant long and requires more public charging stations, even considering the option of charging at home.

There are several major parties who invest in EV charging stations. The government invests in charging stations in public facilities such as hospitals and schools due to the environmental consideration. The business runners of grocery stores and

[1] Level 1, 2, and DCFC are the mostly widely deployed classes of chargers. For the information of other classes, the information can be found at: http://standards.sae.org/j2836/2_201109/.