Applied Energy 258 (2020) 114061

Contents lists available at ScienceDirect

Applied Energy

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

Evaluating the importance and impact of user behavior on public destination charging of electric vehicles

Marc Schmidt*, Philipp Staudt, Christof Weinhardt

Karlsruhe Institute of Technology, Kaiserstr. 12, 76131 Karlsruhe, Germany

HIGHLIGHTS

- A definition of destination charging with extended view on user behavior is proposed.
- Losses in potential demand associated with user behavior are formulated and quantified.
- Charging station operators are capable of counteracting losses caused by user behavior.
- Arrival and dwell time have a strong impact on demand covered by supermarkets.

ARTICLE INFO

Keywords:
Electric vehicles
Destination charging
User behavior
Charging station

ABSTRACT

With an increasing number of electric vehicles (EVs) on the road the need for charging stations increases. Some of these stations are placed at the destinations of drivers rather than along the route of their trip. The aim of this paper is to highlight the importance of user behavior in the context of public destination charging and to provide an extension for existing evaluation methods. We identify losses in demand and potential revenue and show how they are influenced by user behavior. Different scenarios are analyzed to demonstrate the effect of single parameters and to quantify their impact on revenue. To demonstrate the interaction between parameters we present a case study on supermarkets in a medium sized German city. The results show that user behavior is an important factor for the economic evaluation of public destination charging stations and therefore needs to be considered in future evaluation methods. In addition, we show that charging station operators have the possibility to counteract losses by providing more charging stations or increasing the charging power.

1. Introduction

In recent past, nations all around the world have defined goals on the number of electric vehicles (EVs) they want on the road within the next years or put a time limit on the sale of fossil fueled cars. For example, Germany has set the target of one million EVs until 2020, Denmark aims for independence of fossil fuels in the transportation sector by 2050, France by 2030.

Reasons for this are the lower overall emissions of EVs [1–3], lower noise disturbances [4] and the local emission free mobility. From a customers perspective, EVs can offer lower operational costs [5,6] and a strong acceleration [4], which is connected to a dynamic driving [7]. As a consequence, the share of EVs is expected to increase over the next years.

Nevertheless, today's adoption of EVs is still low. With a share of 0.7% among all cars in Germany [8], drivers of EVs can be seen as the innovators in the technology adoption life cycle. Innovators are characterized by being able to cope with a high degree of uncertainty and are therefore able to adjust to the new characteristics of EVs. With an increasing adoption of EVs, the share of drivers that seek mobility without compromises grows. It has to be expected that the majority of future drivers is not willing to accept as many limitations of EVs as the innovators. Today's limiting factors of EVs are the absence of an adequate charging infrastructure, their limited range [9] and slow charging process [10]. In addition, only 60% of car owners in Germany have access to off-street parking, whereas 40% do not have access to a dedicated parking spot [7]. Even though it can be assumed that charging infrastructure availability increases with the number of EVs, there will still be a great number of EV owners reliant on public charging infrastructure. Especially with the longer time for charging, this might cause an inconvenience in the mobility pattern due to additional trips or extended stays at a charging location. Therefore, the demand for

* Corresponding author.
E-mail address: marc.schmidt@kit.edu (M. Schmidt).

https://doi.org/10.1016/j.apenergy.2019.114061
Received 30 June 2019; Received in revised form 27 September 2019; Accepted 23 October 2019

public charging stations that integrate into the mobility pattern of EV driver increases.

In addition, inexperienced EV drivers are more affected by range anxiety. Range anxiety describes a driver's fear of not being able to reach their destination and limits the adoption of electric vehicles [11]. This fear can be addressed and reduced through various methods, such as increasing the range of EVs or by ensuring a high State of Charge (SOC) at the beginning of a trip.

Whilst charging infrastructure cannot influence the range of a car, it can increase the SOC at the beginning of a trip if the car is plugged in. This requires charging infrastructure at locations close to the driver's parking spot. Additional trips to public charging infrastructure can be seen as an burden that needs to be minimized. Several studies have already focused on optimal charging infrastructure localization in order to minimize additional trips [12,13] or reduce the walking distance to charging stations [14]. In the scenario presented in this paper, we define the optimal outcome as a charging infrastructure network where no additional trips are necessary as the energy charged at the destination of each trip is adequate to fulfill the next journey. This kind of charging is also referred to as destination charging.

The term "Destination Charging" is frequently used in literature and industry but definitions are rather rare and variable. Tesla has a product called Destination Charging that allows Tesla drivers to charge their car upon arrival at selected hotels, restaurants and shopping centers [15]. The authors of [16] define destination charging as charging sessions that happen after an EV arrives at its destination, including home and workplace charging. In the work of [17] destination charging is defined as charging sessions from 10 to 180 min at amenities such as supermarkets, gyms, cinemas and shopping centers, therefore excluding charging at home or at work. The authors of [18] follow Tesla's differentiation between super- and destination charger and define the latter as charging at malls, hotels, residential communities and other public places, where parking is possible.

The definitions provided differ mainly in two aspects: First, the destinations covered may either only include public locations or can be extend to charging at home or work. The second aspect focuses on the time spend for charging. Whilst most definitions do not include a time limit, there are also definitions providing an upper and lower bound. In addition, none of the definitions however consider the customer's need for charging. Given the partly contradicting use of the term destination charging in literature and the missing focus on user behavior this paper proposes a new, more detailed definition:

Definition. Destination charging describes the charging of electric vehicles in places where the need for parking is independent of the state of charge of the vehicle. The primary aim of the driver is reaching and parking at a destination whereas charging can be considered an on-top service.

Possible destinations are hotels, supermarkets or gyms but also home or work. Since the latter two are private and semi-public they differ in their usage. In this paper, we focus on locations that are public which is referred to as *public destination charging.* Charging sessions not covered by the term destination charging are those where EV drivers charge in the middle of a trip to extend their range, for example at rest stops close to the highway. This kind of charging is also referred to as urgent charging [16] and is not covered by this paper.

The definition of destination charging proposed in this paper extends current literature with a new view on parking and charging at a location. It implies that the process of parking can be seen as being controlled exogenously by the necessity of a trip for a specific activity. Therefore, the charging session at the parking destination has to occur within the boundaries set by this activity. In contrast to recent literature, this definition of destination charging clarifies that a user's decision to park is independent of the availability of charging stations. As charging is independent of the stay at a location, drivers will not need to queue in front of charging stations or return to their car early in order to start a charging session. As a consequence, we show that it is essential to consider user behavior at a location to both provide customers with the appropriate charging infrastructure as well as to ensure an economic operation of charging infrastructure in the context of public destination charging.

In this paper we focus on the influence of user behavior at a specific location on the revenue of the charging stations by determining the demand of EVs covered. We show that aggregating the demand of all vehicles arriving at the location is not an adequate estimator for revenue of the charging infrastructure as occupied charging stations and early departures are not considered.

We also show how different user behavior influences the expected revenue and present a case study to illustrate the effect of user behavior on the expected revenue of charging infrastructure located at supermarkets.

The contribution of this paper is based on the analysis of the following research questions:

1. Is user behavior a relevant factor for the economic evaluation of destination charging locations?
2. How does user behavior affect the demand of customers covered and how can charging station operators influence the impact?
3. Does user behavior within the sector of supermarkets influence the economic evaluation of the location?

In addition, we provide insights on how to gather the relevant information for a large scale evaluation as well as how to extract arrival times for a given utilization.

This work is structured as follows. In Chapter 2 we present different approaches to evaluate locations for charging infrastructure and categorize them by their perspective and location accuracy. In Chapter 3 the user behavior model and the losses connected to user behavior are introduced. We perform a scenario analysis in Chapter 4 to investigate how user behavior influences the economics of charging infrastructure and how charging station operators can counter potential losses. A case study is presented in Chapter 5 to demonstrate the impact of user behavior in a real world environment within the domain of supermarkets. In Chapter 6 we conclude our findings and indicate potential extensions to our research.

2. Related work

Optimal siting of electric vehicle charging infrastructure is one of the key drivers for EV adoption and is extensively analyzed in literature. In addition to a wide variety in underlying data, assumptions on drivers charging behavior and future EV adoption, research also follows a spectrum of objectives when siting charging stations. In this section we focus on the different approaches to evaluate the location of charging stations and their fit for destination charging. The papers are grouped by their main objective.

Welfare. One method to determine the optimal location for charging is to optimize the welfare of the whole system. The authors of [19] determine the optimal location for charging infrastructure by minimizing the social cost of the whole charging system. They define social cost as the aggregation of annual investment and O&M cost for charging stations, annualized grid reinforcement cost and annual network losses cost. Their evaluation is based on eight typical days over a year and parking behavior is aggregated to three different scenarios. User behavior at a particular location is neglected. The authors of [20] site a given number of public charging stations to maximize social welfare for an average hour. The social welfare includes the expected utility and the charging expenses of the driver, the total generation cost of electricity and the total construction cost for the charging network. By looking at an average hour, consequences through different utilization of the charging station during the week are not covered.

Convenience. One of the advantages of destination charging is it's ability to blend into EV owners' mobility pattern without the need for