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Planning of electric vehicle infrastructure based on charging reliability and quality of service

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This paper presents an optimization model for charging station placement in order to minimize the overall cost by satisfying the charging reliability and quality of service expected by electric vehicle owners/drivers. To better understand and illustrate the problem's complexity, set modeling is used to represent the road network and the electric vehicle driving trajectories. By involving the Euclidean distance, this optimization model also considers the charging reliability as well as the driving range limitation of electric vehicles. The disposable charging time of electric vehicle owners/drivers is reflected by incorporating the new Quality of Service index. The numeric results illustrate the application of the proposed optimization in achieving the minimal cost of charging station locations while also achieving both charging reliability and expected quality of service through the analysis of electric vehicle owners'/drivers' behavior.

1. Introduction

Today, transportation is the major contributor to urban air pollution due to the exhaust gases of conventional liquid-fueled vehicles, [1]. Above all, emissions are expected to rise even more in the upcoming years and the level of urban noise is expected to increase, especially in developing countries. Electric vehicles (EVs) can play a significant role in addressing the challenges of mitigating the environmental impact of the transportation sector on urban air and noise pollution, improving the power system reliability [2], and satisfying the demand for transportation services. Low-carbon fuels, renewables and massive deployment of EVs are taking higher importance in climate change mitigation, [3]. The affordability of EV purchase i.e. the extent to which the price of the EV is affordable to the potential buyer; low emissions, operation and maintenance costs; technological improvements in battery manufacturing; social-media popularity; type of EV i.e. its purpose (e.g. taxis); charging technology/battery swapping or any other recharging mechanisms and higher environmental awareness are the key factors that contribute to EVs' growing practicality and popularity. To ensure widespread EV use and unlimited EV mobility, however, cities must invest in the proper expansion and reinforcement of the electrical power grid as well as the establishment of charging station infrastructure.

Right now, authorities around the world are considering different policies that promise to alleviate climate change. Electromobility has been recognized as an appealing and viable option, and many research works that consider the future of EVs have been supported. Increasing the number of EVs on the road would tax the power grid since batteries need to charge. Battery charging raises additional concerns relating the driving range of the EV. The driving range per charge and long charging time represent major limitations of the EVs. Eventually, the driving range is a function of charging time, driving behavior and road network. For fostering the use of EVs in the near future, there is the need to compensate the driving range limitation of the EVs by establishing a distance reliable charging infrastructure. Random distribution of charging stations (CS) and forming an occasional charging infrastructure would represent a significant barrier in widespread adoption, since it would cause scarcity of convenient charging locations. In Ref. [4], fundamentality of the energy infrastructure problem regarding telecommunications, railways for trains, electricity grid and natural gas pipelines in the energy sector is discussed and it is shown that new infrastructures are built when required to overcame strategic needs. Also in Ref. [5], the scarcity of having refueling facilities in convenient locations is argued. It is pointed out that the main barrier for adopting alternative fuel vehicles is the huge cost of

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developing a dispersed recharging infrastructure. Authors point out the importance of involving new methods to minimize the costs of developing an alternative fuel recharging/refueling infrastructure.

Up until now, literature has recognized a variety of discrete location models. The taxonomy of discrete location models fall under three categories: coverage, median and dispersion models as noted in Ref. [6]. The coverage discrete location model relates to the discrete set-covering problem, as explained in Ref. [7], and it is stated as discrete location set-covering problem (LSCP), where by definition, the problem is to find the minimum number of facilities to cover the demand-represented as passing flows or potential customers aggregated as area points. The first discrete set-covering model was introduced in Ref. [8], where it was used to find the minimal number of emergency ambulance vehicles to cover (distance, time criterion) the demand nodes by at least one emergency vehicle. In Ref. [9], the LSCP was used to develop a model to determine recharging locations using an integer program with a case study validation. This model was developed to enhance the initiative to mitigate air pollution. Additionally, sensitivity analysis was performed to seek the minimum recharge time and length of stay at each site. The objective function is to minimize the charging stations' allocation cost. Constraints are set on the candidate sites capacity. In Ref. [10], the same methodology for battery exchange stations is applied, which is a valid time-saving option for EVs. In Ref. [11], the authors use the concept of set-cover for proposing a refueling-station-location model using a mixed-integer programming method, based on vehicle-routing logic. In Ref. [12], the concept of set-cover and vehicle refueling logic is used to propose a hybrid model with dual objectives, using a mixed-integer programming method to locate refueling stations at minimal cost. In coverage discrete location models, it is supposed that unlimited resources are available-a rare case in reality. Therefore, the extended version of the problem is defined as maximal covering location problem (MCLP), where the total amount of population served is maximized within a maximum distance or time criterion by a predefined number of facilities (limited finances). In Ref. [13], a model for maximizing the covering of the demand clusters during morning or evening peak hours is proposed by the constraints set on the number of charging stations. It represents improvement on the set-covering location problem. In Ref. [14], a set-covering location model is proposed coupled by a simulation process to determine where to locate electric vehicle charging stations to maximize their use by privately owned EVs. The objective function is set on maximizing the number of charged EVs or the total electrical energy re-charged by setting the constraints on the charging capacity of the candidate locations. In Ref. [15], a parking-based set-covering model is introduced, where the objective function is based on the minimization of trips to the charging stations by satisfying the demand, aggregated as nodes of attractive areas subject to the number of charging EVs. In Ref. [16] the authors propose a customer demand set-covering model, i.e. an optimized algorithm for location scheme for electric charging stations. In Ref. [17], a multi-objective electric vehicle charging station planning method is proposed that ensures charging service, while also reducing the power losses and voltage deviations of distribution systems. Also, a battery capacity constrained EV flow capturing location model is proposed to maximize the EV traffic flow that can be charged, given a candidate construction plan of EV charging stations. In Ref. [18], set-covering location modeling is used and the existing traditional gas station network as the candidate sites to determine the distribution of the charging and battery swap stations. The objective function in Ref. [18], minimizes the total cost of deployment of the charging stations, by including the transformation cost of the gas station into a grade noted charging station subject to the number of charging points that should cover the demand points and the capacity of the charging stations. Recently, in Ref. [19], the authors have presented an optimization model for selecting public charging stations by maximization of the electrified vehicle-miles-traveled for potential environmental benefits. The public charging demand is modeled by using large-scale vehicle trajectory data. To verify the model, the public charging infrastructure for the city of Beijing is used as a case study. In Ref. [20], a review of recent trends in optimization techniques for plug-in hybrid, and electric vehicle charging infrastructures is made. It is noticed that the growth of the smart grid technologies depend upon the recently introduced electric vehicle charging infrastructure services. In Ref. [21], it is demonstrated how driving patterns databases and data mining can be used to appropriately design the charging infrastructure for EVs. It provides a developed model and focuses on the valuable potential of the proposed methodology to support the future policies for designing alternative fuel infrastructures in urban areas. In Ref. [22], a new model and framework for the improved determination of charging infrastructure allocation for occasional battery charging is presented. The concept of occasional recharging is shown which is used to provide additional usable battery energy to the system without any additional disturbance of processes, while using existing process sequences and process interruptions in optimized infrastructure allocations.

The literature review referenced above is entirely committed to discrete location set-covering problem (LSCP) based optimization models for charging stations placement. An added note with respect to the charging stations location and charging infrastructure establishment: in general conclusion, the research filed on charging infrastructure establishment, points on a gap in the consideration of the expected quality of service of the charging infrastructure characterizing the EV drivers' needs and behavior. The quality of service depends on whether or not the nearest charging station is within some pre-defined known distance or charging time. The goal for this paper was to put together the available charging time of the EV drivers when dealing with longer trips and to locate charging stations within the driving range of the EV that satisfies mobility limitation. It is this paper's challenge to improve the general set-location optimization models by introducing quality of service, defined as expected charging time, while minimizing the overall charging infrastructure placement cost. First, the paper's idea is prioritized by lowest cost, in order to reliably satisfy the needs of the charging service, indicated by the EV drivers' behavior and to resolve range limitation (i.e., to ensure charging reliability, and to consider the expected quality of charging service, with the intention of dealing with the request of available charging time per charging service when driving for longer distances).

This paper develops a set-covering location problem based linear integer optimization model for determining locations of charging stations by minimizing the overall charging infrastructure cost subject to the charging reliability due to the driving range limitation and demanded quality of service as a consequence of the disposable charging time of the EV users. Its main advantages when compared to the existing LSCP based optimization location models presented in Refs. [9–12], are:

- Ensured charging reliability by placing at least one charging station within the driving range of the EV drivers, based on the distance criterion, which is defined by the Euclidean distance between two points and EV drivers' driving range. The driving range is a key factor for determining the locations of charging stations for completing longer trips. In this paper, the 'distance to empty' of the EV drivers' which depends on uncertainty factors such as speed of driving, road terrain, traffic, air conditioning, is included in drivers' driving range, R_v. Since, each v-th