Applied Energy 182 (2016) 39–46

Contents lists available at ScienceDirect

Applied Energy

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

A demand-side approach to the optimal deployment of electric vehicle charging stations in metropolitan areas

N. Andrenacci *, R. Ragona, G. Valenti

ENEA – Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Rome, Italy

HIGHLIGHTS

- A demand-side approach to the location of charging infrastructure problem is discussed in the paper.
- The analysis is based on a large data-set of private vehicle travels within the urban area of Rome.
- Cluster analysis is applied to the data to find the optimal location zones for charging infrastructures.
- The daily energy demand and the average number of users per day are calculated for each and every charging infrastructure.

ARTICLE INFO

Article history:
Received 15 January 2016
Received in revised form 14 April 2016
Accepted 31 July 2016
Available online 25 August 2016

Keywords:
Electric mobility
Electric charging station deployment
Big data analysis
Electric vehicle energy requirement
Cluster analysis
Electric vehicle simulation

ABSTRACT

Despite all the acknowledged advantages in terms of environmental impact reduction, energy efficiency and noise reduction, the electric mobility market is below expectations. In fact, electric vehicles have limitations that pose several important challenges for achieving a sustainable mobility system: among them, the availability of an adequate charging infrastructure is recognized as a fundamental requirement and appropriate approaches to optimize public and private investments in this field are to be delineated. In this paper we consider actual data on conventional private vehicle usage in the urban area of Rome to carry out a strategy for the optimal allocation of charging infrastructures into portions (subareas) of the urban area, based on an analysis of a driver sample under the assumption of a complete switch to an equivalent fleet of electric vehicles. Moreover, the energy requirement for each one of the subareas is estimated in terms of the electric energy used by the equivalent fleet of electric vehicles to reach their destination. The model can be easily generalized to other problems regarding facility allocation based on user demand.

1. Introduction

Road vehicles are acknowledged to be significant sources of a range of pollutants, and they have been estimated to contribute to about one-fifth of the EU's total emissions of carbon dioxide (CO_2), the main greenhouse gas [1].

Electric mobility is an important option to reduce environmental impacts and climate gas emissions from transport: in fact, it is recognized as energy efficient, does not cause local emissions, reduces noise and may benefit from increasing renewable energy production in the future.

Moreover, electric vehicle (EV) batteries may provide auxiliary storage capacity for the electricity grid, further reinforcing the integration of renewable energy conversion technologies in the national electrical grid.

Despite all these advantages, the spread of the electric vehicle market is somewhat below expectations. This could be ascribed to a variety of factors, such as financial questions (e.g. car cost) and vehicle usability, which involves customer concerns on range [1–3] and a lack of widespread charging networks [4].

The importance of a widespread charging network of alternative fuel has been outlined recently in the European Commission communication on clean power for transport (see Ref. [5]) and in the proposal for directive on the deployment of alternative fuels infrastructure (see Ref. [6]), which provide a legal framework to promote the deployment of the recharge network for EVs on a European basis.

Many other national authorities and international organizations have been issuing reports or guidelines to provide the essential information and resources required to implement electric vehicle

* Corresponding author.
E-mail addresses: natascia.andrenacci@enea.it (N. Andrenacci), roberto.ragona@enea.it (R. Ragona), gaetano.valenti@enea.it (G. Valenti).

http://dx.doi.org/10.1016/j.apenergy.2016.07.137
0306-2619/

charging infrastructures. For example, the Centre for Energy Advancement through Technological Innovation (CEATI), which includes more than 120 worldwide electric and gas utilities, governmental agencies and provincial and state research bodies, issued an online resource [7] for Canada, and the Electric Power Research Institute (EPRI), which comprises more than 1000 electric utilities, firms, government agencies, corporations and public or private entities engaged in some aspect of the generation, delivery or use of electricity, published in this field a dedicated report [8].

Moreover, theoretical studies have been conducted to develop strategies for creating intelligent charging grids, taking into account different parameters like costs, minimization of distances, charging technologies and intelligent V2G (vehicle-to-grid) and G2V (grid-to-vehicle) energy management [9–12].

In particular, some studies considered techniques of operations research, including linear/nonlinear programming and Multi-Criteria Decision Making (MCDM) methods; for example Guo and Zhao [13] used MCDM to consider some important criteria for site selection. An approach based on the solution of a charging station minimal cost model using a genetic algorithm was proposed by Li et al. [14]. Sadeghi-Barzani et al. [15] took in consideration various factors as development cost, EV energy loss, electric grid loss in their Mixed-Integer-Non-Linear approach for optimal placing and sizing of fast charging stations. The integration of renewable energy sources into DC fast charging architecture was considered in Capasso and Veneri [16]. A method for optimal placement of charging stations with minimum total transportation distance for integration of EVs into grid was presented in Xu et al. [17]. An optimization-based model, assuming the estimated EV consumptions in urban cycles as an input to the mathematical procedure (an integer linear model) was developed in Baouche et al. [18]. A big-data collection containing travel patterns of a taxi fleet in the city of Beijing has been used to identify the charging infrastructure locations in Cai et al. [19]. A demand-side approach has been proposed in Frade [20], where a maximal covering model has been used to optimize a hypothetical electric vehicle fleet demand, and in Gonzales [21], in which a simulated behavior for EVs has been analyzed to find the recharge strategy that minimizes the cost for EV owners.

The purpose of this paper is to analyze real travel patterns on private vehicle usage, extracted from a big collection of vehicular travel data, in order to identify a strategy for the optimal allocation of charging infrastructures in an urban area that will meet the user needs (demand-side analysis). The analyzed subset contained 57,890 trips, corresponding to roughly 745,660 km of a week of the year 2013. The case study considered the city of Rome, and the research was funded by the Italian Department for Economic Development (Ministero dello Sviluppo Economico) inside the project "Electric System Research" (Ricerca di Sistema Elettrico).

In order to identify the likely patterns for a potential electric vehicle fleet, we analyzed existing vehicular travel data collected in the urban area of Rome to study the behavior of conventional fuel vehicles. This data was considered to simulate driving and charging behavior under the assumption of a complete switch to an equivalent fleet of EVs.

Since the allocation of a charging station depends on many factors, among them the availability of a specific space in the location and the topology of the underlying power grid network, we will not, in the first instance, identify the exact locations of the charging stations. Instead, we aim to divide the urban area of Rome into subareas of different amplitude, each one served by a charging infrastructure, which result from the application of an optimization criteria of minimization of the total distances from the subarea centres (centroids).

Moreover, the energy requirement for each suburb will be estimated in terms of the electric energy spent by the equivalent fleet of EVs.

To the best of our knowledge, two other papers have conducted similar work based on the analysis of a large amount of traffic information by applying different methodologies. In De Gennaro et al. [9], the proposed methodology to allocate recharge infrastructure is based on real-world driving pattern data similar to the data we have used in this work. However, the analysis is conducted on the basis of different criteria and assumptions, starting from a list of existing points of interest as candidates for recharge facilities.

In Ip et al. [22], the Cluster Analysis methodology is applied on data collected from a variety of sources to generate a demand cluster, using constraints based on a criterion of cost optimization.

The novelty of our work lies in the following:

- a detailed analysis of the energy consumption, based on experimental and simulated data for two EV commercial models has been performed;
- the speed profiles for the analyzed trips have been carefully reconstructed, inferring from the GPS data or from the speeds of other vehicles passing on the same link in a given time lapse. In this way, the energy demand for each trip can be estimated taking properly into account the kinematic variations;
- an optimal distribution in the urban area of the potential users and the energy load for the charging events, using a fuzzy clustering approach and a suitable modelling for energy consumptions, were considered.

2. Proposed methodology

In this paper, we propose a methodology that is based on the analysis of a large sample of real traffic flows in the urban area of Rome, the sample representing nearly 6% of the entire private vehicular fleet. At this first stage, we suppose a complete switch of the sample from conventional to electric mobility and that the applied analysis results are linearly dependent on the number of vehicles in the fleet, so that a different percentage of EV penetration will cause a linear rescaling of the results.

The data refer to privately-owned conventional fuel vehicles that have been equipped with an acquisition device, which records information on a trip, through GPS, and sends it to a data processing center via GSM/UMTS channels.

A two-step procedure is applied to the available data sample:

(1) A cluster analysis is performed on the destination GPS coordinates of all the trips ending in the Rome urban area. At this stage, based on the final destination, each trip is assigned to a cluster, which identifies a urban subarea. The set of clusters obtained from the analysis represents an optimal partition of Rome's urban area from a demand point of view, and the charging infrastructures are associated with the cluster mean points (centroids).
(2) The conventional fleet sample is replaced by a hypothetical electric fleet. For each cluster, the total energy request for mobility purposes (in kWh) is estimated as the sum of the energy spent by all the trips ending in the cluster, all trips supposed to be performed in electric mode.

The identification of the charging stations with the cluster centroids has a pure mathematical meaning. In order to determine their exact location, a detailed analysis of the local topology, the urban policies and the electric distribution grid must be carried out, which is beyond the scope of the present work.

The proposed methodology relies on the analysis of a large driving pattern database that is described in detail in the next session.