Renewable and Sustainable Energy Reviews 80 (2017) 98–108

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Electric vehicle charging infrastructure planning in a road network

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ARTICLE INFO

Keywords:
Electric vehicles (EVs)
Electric charging station network
Location problem

ABSTRACT

The implementation of a charging infrastructure network is the necessary prerequisite for the diffusion of Electric Vehicles (EVs). In this paper a methodology to calculate the required number of charging stations for EVs and to set their position in a road network is proposed. The aim is to planning the distribution of services area to host charging infrastructures. Using the demand (the flow of EVs) and the supply (the road network where they will be positioned) through a two-level model were the locations initially identified (first level) and thereafter the number of charging stations for each service area (second level) evaluated. The paper deals with the intersection of three main topics: the vehicle technologies (engine and battery pack specifications), the charging station characteristics and the EVs flow. After verifying the model and the solution procedure on a test road network, the methodology is applied in a high dimension case, considering the Italian highway network.

1. Introduction

The transportation sector largely depends on liquid fossil fuels, in itself represents an important part of the economy: in the EU it directly employs around 10 million people and accounts for about 5% of GDP (Gross Domestic Product). In 2013, the transport sector contributed almost one quarter (24.4%) of total EU-28 greenhouse gas emissions [1]. In the last years, a greater attention has been paid to environmental problems thanks also to the issue of the "White Paper" by European Commission. The challenge is to break the transport system's dependence on oil without sacrificing its efficiency and compromising mobility. Furthermore it establish a system that enhances competitiveness and offers high quality mobility services. It aimed to achieve a sustainable and cooperative transport policy and one of its targets is the 50% reduction within 2030 of the internal combustion engine vehicles and the total elimination within 2050. The main support factor for the achievement of these goals is the spread of the EVs but no change will be possible without an infrastructures network that supports the launch of full EVs contributing to maximize positive impacts.

In literature, a lot of works [2,3,5–45] deal with the charging stations for alternatively powered vehicles, providing different approaches to size and place the charging infrastructures but there seems no evidence about the use of correlation between energy of vehicle's traction battery pack and technical characteristics of the charging station. This "influence" is considered extremely important because it conditions directly the charging time and indirectly the number of charging stations to be installed in a given road section. Another main element of analysis is represented by the EV flows. Although in literature some works use the flow of vehicles as variable in calculations, it is never reported to actually circulating electric vehicles. In this paper the vehicles are related to the EV registration data for each geographical area and some projections of the reference market are introduced. Some recent articles analyzing positioning procedures referring to the latest generation of charging infrastructure (fast charge) even if the circulating electric vehicles in most cases does not allow this type of charging. In this paper were made different assessments considering a wide range of powers available starting from the domestic charging (3.7 kW).

Therefore the vehicles technologies used to charge the battery pack, the technologies of the charging stations and the vehicle flow analysis are integrated in a single approach (Fig. 1). With regards to the vehicle technology will be discussed: i) the power range that the vehicle is able to accept to recharge the battery pack and ii) the energy of the battery pack in order to evaluate the vehicles autonomy. Following the directives of the Italian National Plan will be evaluated the power range that charging stations are able to supply and the maximum number of sockets for each [4]. The flow refers to the volume of vehicles traveling on the road network considered. This measure influence the sizing and the geographical distribution of the charging stations. Furthermore it highlights that it is proposed also an application on a real network not limiting the analysis on a toy network (Sioux Falls test network, [5–7]).

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http://dx.doi.org/10.1016/j.rser.2017.05.022
Received 25 May 2016; Received in revised form 3 March 2017; Accepted 5 May 2017
1364-0321/

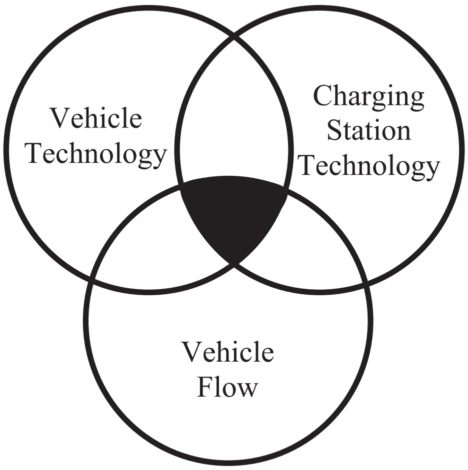

Fig. 1. The intersection of the topics dealt in the paper.

The paper is structured as follow. The literature review is reported in Section 2; in Section 3 the model, distinguishing the supply (Section 3.1) and the formulation (Section 3.2), is proposed; in Section 4 the algorithm is described; in Sections 5 and 6, an application in a test network and in a high dimension network are, respectively, reported. Finally the conclusions with a resume of the obtained results.

2. Literature review

Increased use of vehicles powered by alternative fuels inevitably focuses attention on the need for an appropriate distribution of the charging infrastructure. The fuel stations allocation can be made using the approaches typical of the facilities location [8]. In general, a location model refers to the allocation of any facility in relation to the users demand in a specific area [9]. When the user is a driver that need to refuel his vehicle, a flow refuelling location model can be formulated to optimize the distribution of fuelling stations minimizing the investments and maximizing the served users [10–16]. Other models are available as the p-median model in [17]. The optimal location of a public charging stations for EV on a road network is explored in [6] where the charging infrastructures are placed considering drivers' spontaneous adjustments and interactions of travel and recharging decisions. In [18], in order to reflect users' charging behaviour, is provided a solution for the location of rapid charging stations in an urban area through a probabilistic remaining fuel range distribution. A set of evaluation criteria for a fast-charging network planning regarding both position and concrete realization is evaluated in [19,20]. The use of real world vehicle travel patterns (11,880 taxis' trajectory data over a period of three weeks) or the analysis of a large sample of real traffic flows in the urban area is also considered extremely important [21,22]. From another point of view some studies analyze the impacts of EVs on the electric grid [5,24–27]. In terms of refuelling, the use of EVs is more constraining than the use of other types of alternative fuelled vehicles because the refuelling time is slower. In literature, models and algorithms are proposed to formulate and solve the location problem related to the electric charging points. Sathaye and Kelley [28] propose a three steps approach based on facility location problem to determinate the minimum value needed of EVs infrastructure for highway corridors. The problem is formulated as a constrained problem (the main restriction is the budget) and it is solved after a Lagrangian transformation. Xu et al. [29] propose a model to configure centralized charging stations with the aim to minimize the total travelled distance by EVs. Xi et al. [30] propose a model to optimize the location assuming a set of fixed points where the charging stations can be built. The optimization allows to evaluate the dimension of the charging station, with the aim to maximize the amount of energy recharged by EVs with a budget constraint. Nie and Ghamami [31] propose a model to planning the charges infrastructures guarantying a high level of service and minimizing the costs. Liu [32] proposes an assignment model to allocate the charging infrastructures in three steps: demand identification, infrastructures assignment, charging station test (to avoid overloads). Zheng et al. [33] propose a two levels model where at the upper level the objective is to locate charging stations and at the lower level an equilibrium traffic assignment is performed. Han et al. [34] present a charging facility planning model to find optimal charger distribution based on the trajectory-interception method analyzing the data collected from the travels of a set of taxi. Dong et al. [35] propose a method, based on genetic algorithm, to planning the charger infrastructure optimizing the location and simulating the driver behaviour and exploring the aspects that influence the refuelling [6,36–38]. EV charging station site selection was studied from sustainability perspective [39] or from charging reliability and quality of service point of view [7]. The European Parliament recently adopted solution for the promotion and support of electric vehicles for people transportation in order to regulate a single European electricity and EVs market [40,41]. Around the world there are many initiatives underway with government support to encourage the adoption of EVs [42]. In the United States BMW, Volkswagen and ChargePoint are engaged to create an electric vehicle express charging corridors on the East and West Coasts with the goal of install fast charge points to support long distance and metropolitan travels with EVs (www.chargepoint.com). Skerlos and Winebrake in their paper described public policies in the U.S.A. for EV penetration with a discussion on three social benefits categories [43]. They suggest that a differentiated subsidy scheme for EVs will maximize social benefits and electric technology penetration. It's needed to elaborated business model even for vehicle-to-grid applications for giving an answer to the main issues of the EV integration [44] and the estimated Return Of Investment (ROI) of a public fast charging station [45]. The Italian Ministry of Infrastructures and Transportation at the same time has issued a document in order to regulate the development of electric infrastructures establishing guidelines on power level ability and charging modes for domestic and industrial charging stations [4].

3. Model

After introducing the supply representation, the model is formulated at two levels: service areas positioning and quantification of the number of charging stations for each area. Fig. 2 shows the logical flow of the proposed model. The highway network is represented with a *graph* $\mathbf{G}(\mathbf{N}, \mathbf{L})$ where $\mathbf{N}$ is the set of nodes and $\mathbf{L}$ is the set of links (assuming a link as an ordered pair of nodes). A *graph analysis* allows to define:

1. a subset of *feasible links* ($\mathbf{A} \subseteq \mathbf{L}$), defined as the set of the links where it is possible insert a service area;
2. two (disjoint) subsets of *nodes*: ($\mathbf{M} \subseteq \mathbf{N}$) (master nodes) are the nodes placed at big cities (assumed as a relevant branching highway) or in singular points (i.e. national borders); ($\mathbf{S} \subseteq \mathbf{N}$) (slave) are the other nodes (i.e. toll booths, highway exit, regional borders).

The *location search* have as input the feasible links, the nodes and a vector of *parameters* $\mathbf{P}$ (the parameters consider vehicular flow and charging stations characteristics) and give as output the *charging station position* and the *number of charging stations* for each service area (see Section 4).

3.1. Supply

Considering the adopted graph representation, it is defined *edge e* the line between two master nodes. An edge is a set of consecutive links between two master nodes that do not crossing another master node