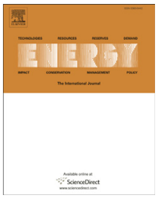
Energy xxx (2015) 1–18

Contents lists available at ScienceDirect

Energy

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



Customer-driven design of the recharge infrastructure and Vehicle-to-Grid in urban areas: A large-scale application for electric vehicles deployment

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ARTICLE INFO

Article history:
Received 14 August 2014
Received in revised form
20 December 2014
Accepted 13 January 2015
Available online xxx

Keywords:
GPS driving patterns databases
Data mining and big data
Battery electric vehicles
Electric energy demand
Points of Interests and recharge infrastructure layout
V2G electric energy load peak-shaving

ABSTRACT

The large scale deployment of electric vehicles in urban environment will play a key-role over the next decades to reduce air-pollutants in densely populated areas, but it will also require the development of an adequate recharge infrastructure. The purpose of this paper is to demonstrate how driving patterns databases and data mining can be used to appropriately design this infrastructure. This application focuses on the Italian province of Firenze, involving about 12,000 conventional fuel vehicles monitored over one month, estimating a fleet share shift from conventional fuel vehicles to battery electric vehicles ranging from 10% to 57%, and a mileage share shift from 1.6% to 36.5%. The increase of electric energy demand from electric vehicles ranges from 0.7% to 18% of the total demand in the province, with a number of charging spots three-to-six times higher than the number of circulating electric vehicles. Additionally the results show that a Vehicle-to-Grid interaction strategy can contribute to reduce from 5% to 50% the average daily electric energy demand in specific locations. This paper provides a description of the developed model and focuses on the valuable potential of the proposed methodology to support future policies for designing alternative fuel infrastructure in urban areas.

1. Introduction

The large scale deployment of EVs (Electric Vehicles) in cities will play a key-role in order to improve air quality in densely populated areas, limiting the negative effects of human exposure to air pollution from transport and reducing the GHGs (Greenhouse Gases) emissions.

The health risks related to air-pollutants are largely addressed in literature [1,2]. As far as pollutants from transport are concerned, the World Health Organisation highlights that drivers, pedestrians and people who live near roads characterised by heavy traffic flows are exposed to exhaust gaseous emissions and PM (Particulate Matter) levels three times higher than background levels, showing that tens of thousands of deaths per year can be attributed to transport-related air pollution, similar to the death toll from traffic accidents [3]. In addition, epidemiology and toxicology literature reviews derive that there is a causal relationship between human exposure to traffic-related primary and secondary gaseous emissions and exacerbation of respiratory and cardiovascular diseases for people living within 500 m from major roads [4]. These findings are confirmed by a large number of similar studies, from different regions of the world, such as [5–8], including the severe problems which are arising in Chinese megalopolis [9].

As far as the GHGs are concerned, it is estimated that road transport contributes to about one-fifth of the total carbon dioxide (CO_2) emissions in Europe, growing by nearly 23% between 1990 and 2010 [10]. In the European area, transport is the only major sector where CO_2 emissions are still increasing [10], and the EU (European Union) is committed reducing them by 20% below 1990 levels by 2020, and by 80–95% by 2050, in order to make a contribution to keep the global temperature increase below 2 °C, under the Kyoto protocol [11,12]. This will imply a whole revision of the mobility plans in Europe, following the guidelines outlined by EC White Paper 2011 [13]. In particular the White Paper identifies ten goals to achieve a 60% reduction target of GHGs emissions from transport below 1990 levels by 2050, including, among the others,

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http://dx.doi.org/10.1016/j.energy.2015.01.039
0360-5442/

Please cite this article in press as: De Gennaro M, et al., Customer-driven design of the recharge infrastructure and Vehicle-to-Grid in urban areas: A large-scale application for electric vehicles deployment, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.01.039

Nomenclature

Acronyms

AC	Alternating Current
BEV	Battery Electric Vehicle
DC	Direct Current
EPA	Environmental Protection Agency
EU	European Union
EV	Electric Vehicle
GIS	Geographic Information Systems
GHG	Greenhouse Gas
GPS	Global Positioning System
G2V	Grid-to-Vehicle
HEV	Hybrid EV
ICE	Internal Combustion Engine
KPI	Key Performance Indicator
IEC	International Electrotechnical Commission
PHEV	Plug-in Hybrid Electric Vehicles
PM	Particulate Matter
POI	Point of Interest
SOC	State of Charge
SUV	Sport Utility Vehicle
V2G	Vehicle-to-Grid

halving the conventional fuel vehicles in urban areas by 2030, and phasing them out in the cities by 2050.

Such reduction of conventional fuel vehicles in cities will imply, on one hand, a shift of people's transportation choices to other solutions (i.e. modal-shift to the public transportation), whereas, on the other, the adoption of low-carbon vehicle technologies, such as Hybrid and Battery EVs (HEVs and BEVs) [14]. According to previous studies, the rate of adoption of these new technologies will depend on several factors, such as socio-economic boundary conditions [15], public incentives [16,17], and vehicles' usability [18–20]. However, although financial aids might play a key-role for the early-adoption of EVs (which are still an expensive technology compared to conventional fuel vehicles), these studies also underline the importance of the availability of a suitable infrastructure capable to support the shift of the energy demand from the oil-sector to the electric energy utilities. The design of this infrastructure is an open topic, and it is fundamental to identify the appropriate approaches in order to optimise public and private investments in this field.

The recent European Commission communication on clean power for transport [21] identifies the development of an alternative fuel infrastructure as a priority, including the electric energy distribution grid as an option for short-range road passengers' and freight transport. Additionally the Proposal for Directive on the deployment of alternative fuels infrastructure [22], highlights the main issues to address in order to facilitate low-carbon vehicles widespread, providing the initial legal framework to promote the deployment of the recharge network for EVs on a European basis.

The development of this infrastructure can be determined by coupling the electric energy demand from electrified vehicles with the electric energy offer. Several studies in literature address the electric energy demand from EVs. For example Kim and Rahimi suggest to model electricity loads from the large scale deployment of PHEVs (Plug-in Hybrid Electric Vehicles) [23], Dhong and Zhenhong, and Smith et al. propose to monitor electrified vehicles using GPS (Global Positioning System) [24,25], whereas Mu et al. propose using Monte Carlo simulation to predict the energy load from EVs over time [26].

As far as network studies are concerned, Xu et al. analyse the statistical trend of network development in cities by deriving an exponential dependence on the activity [27] and Ortega et al. propose to monitor the network development by means of GIS (Geographic Information Systems) technologies [28]. Additionally survey data might be also used to support infrastructural studies [29], exploring intelligent grid management solutions [30], to address the impact on power system operation, market and security policies for BEVs (Battery Electric Vehicle) [31–34] as well as their integration within renewable energy systems [35,36] and their use as flexible loads [37], contributing to the development of methods to enhance the stability of the electricity grid together with intelligent V2G (Vehicle-to-Grid) and G2V (Grid-to-Vehicle) energy management systems, (§ 13 of the EC Proposal for Directive [22]).

Although these studies provide useful insights into the topic of the electricity network design and integration with electric mobility, they all provide general results, without going into a detailed analysis of the energy demand-offer events, which is the basis to design an intelligent, customer-driven recharge infrastructure network for EVs.

Based on this consideration, the purpose of this paper is to provide the scientific community with the results of a model capable to design and size the recharge infrastructure for EVs in high detail, based on a large database of real-world driving patterns. The novelty of this approach consists in using, for the first time, real-world driving and parking events coupled with data mining to identify suitable locations for charging spots based on existing POIs (Points of Interest) databases and a minimum-distance criterion. The developed approach identifies a KPI (Key Performance Indicator) and a repetitiveness index per each considered location, and derives the number of charging spots and the electric power to be installed to meet the potential customers' demand.

The work relies on previous studies from the authors [38–40], and is carried out for the Italian province of Firenze, over an area of approximately 9600 km^2, currently served by the most developed recharge infrastructure in Italy [40]. The analyses involve approximately 15 million kilometres from about 12,000 conventional fuel vehicles, monitored for a period of one month by means of on-board GPS devices. The results present the layout of the derived recharge infrastructure network, by considering three different types of EVs, four different recharging strategies and different fleet scenarios. Additionally a V2G interaction strategy has been implemented at the charging stations level, to explore the potential of sharing small amount of energy from the battery of the parked vehicles to shave localised peaks of electric energy demand. The results are compared with the indications from Refs. [21,22].

This paper provides a full description of the developed model, focussing on the valuable potential of such methodology to support an intelligent and customer-driven planning, design and size of the recharge infrastructure network for EVs, representing a new insight towards future alternative fuel infrastructures for low-carbon vehicles.

2. Background information and methodology

2.1. Driving patterns database and electric vehicles recharging behavioural models

This study relies on a large driving patterns database from the Italian province of Firenze, an area with nearly one million inhabitants and 684,000 registered vehicles [38]. The database contains mobility data of 40,459 conventional fuel vehicles, equal to

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