Energy 87 (2015) 10–20

Contents lists available at ScienceDirect

Energy

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

Enabling solar electricity with electric vehicles smart charging

Pedro Nunes [a,*], Tiago Farias [b], Miguel C. Brito [a]

[a] IDL – Instituto Dom Luiz, University of Lisbon, Portugal
[b] IDMEC – Instituto Superior Técnico, University of Lisbon, Portugal

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form
9 April 2015
Accepted 10 April 2015
Available online 4 June 2015

Keywords:
Electric vehicles
Solar photovoltaic
EnergyPLAN
EV smart charging
Energy scenarios
Energy system

ABSTRACT

It has been shown that a long term sustainable energy system based on a high penetration of solar photovoltaics requires massive deployment of day charging electric vehicles to make use of the excess solar electricity generation at sun peak hours. In this paper the synergy between these technologies is further explored, determining the minimum penetration levels that allow fulfilling the climate and energy targets. Simulations for a case study of Portugal in 2050 using an electric vehicles smart charging approach show that a 100% renewable energy based electricity supply is possible with certain photovoltaics and electric vehicles combinations and that the environmental targets to reduce carbon dioxide emissions are just reachable with significant electric vehicles market share. The notion that vehicle charging will have to take place during working hours to maximize petroleum displacement is reinforced.

1. Introduction

This article analyses the positive interactions between a high penetration of solar photovoltaics (PV) and the deployment of electric vehicles (EVs) in future energy systems [1] having as departure the European context. To contribute to limit climate change below 2 °C[1] [2], the European Union (EU) targets an overall greenhouse gas emissions reductions by 80–95% until 2050[2] [3]. It is only achievable by the intensive use of renewable energy sources (RES) and major alterations in transportation, since energy and transport sectors are the two biggest greenhouse gases (GHG) emitters in the economy[3] [4].

In the economy's decarbonization, electricity will play a main role, given its increasingly importance as an energy vector in modern societies [5] and its potential cleanliness when produced using RES. In particular, solar electricity generated from PV technology appears to be in the future the most attractive form of decarbonized electricity generation due to its noiseless nature, scale flexibility, simple operation and maintenance [6] and price competitiveness trajectory [7],[4] bringing PV on the verge to compete with household electricity prices [8]. For this, solar PV is projected to be the dominant source of electricity in a global warming limiting scenario [9].

Within this framework, EVs[5] are a key technology from the demand side, since they are much more efficient than the internal combustion engine (ICE) [10] models and potentially much cleaner on a well-to-wheel analysis [11]. Carbon footprint of EV driving is directly related to the electricity from which the batteries are charged, which, on the limit, can be 100% carbon free, making EVs the most promising solution to reduce emissions from vehicles [12].

For these reasons, PV is expected to undergo mass adoption in the following decades across the globe [9] while EV use is also

* Corresponding author. Tel.: +351 93 301 69 77.
E-mail address: pmnunes@fc.ul.pt (P. Nunes).

[1] Compared to pre-industrial levels.

[2] Compared to 1990 levels.

[3] The energy sector presently is responsible for the biggest share, approximately 30%, of GHG emissions in the EU [68] and transport is right after, responsible for around a fourth, with the road transport alone answering for a fifth of total emissions [4]. For the time being, transport sector is still a growing source of GHG emissions, with a substantial 36% increase over the past two decades, putting it presently 8% above the 1990 level [4].

[4] Competitiveness is assessed by grid parity: PV will reach it when the electricity produced by a PV system throughout its lifetime is at least as profitable as buying electricity from the grid [7]. Grid parity has already been partially reached in Spain, Germany and Italy [69] and due to the declining PV levelized cost of energy it is expected that the same happens gradually in the rest of the European countries [70].

[5] In this paper, EV refers to electric vehicles in general, comprehending pure electric vehicles, i.e., vehicles propelled solely by electricity, with no internal combustion engine used for propulsion, and plug-in hybrid electric vehicles.

http://dx.doi.org/10.1016/j.energy.2015.04.044

expected to take off [13], which will lead to well-known and relevant impacts on the national energy systems, e.g. possible mismatch between production and consumption of solar electricity and higher electricity demand for EV mobility. Abundant non-dispatchable renewable energy, whose output is conditioned by meteorology and therefore fluctuating, may have to be curtailed or, when similar amounts of variable generation are installed in surrounding markets, exported at low prices [14]. Hence, the installation of storage devices to absorb this energy is highly beneficial [15]. Within this frame, the EVs, with their large battery capacity[6] if seen as a whole, may be an answer to avoid increasing worldwide excess of energy [16]. In fact, the most significant impact on the electricity system of EVs is their ability to assist the integration of renewable energy into existing power grids [17]. For a review on this subject, see Richardson [17]. Previous works addressing specifically the integration of solar PV and EVs are for example [18], addressing the co-benefits of large scale plug-in hybrid EVs and solar PV deployments, and [19], addressing the combination of PV energy and EVs under different charging regimes.

In this work this topic is addressed building upon [1], which may be seen as a companion article. It explored the possible complementarities between wind and solar power and EV deployment using a non-smart day and night charging strategies. It was shown that CO_2 emissions targets can only be achieved with high levels of PV penetration and EVs day charging, reinforcing the need for day time charging infrastructures [20], presumably at or near work facilities [1]. A future energy scenario for Portugal in 2050 was used as case study. This country is especially appropriate to test the interaction of these two technologies, since it has a substantial solar resource availability[7] [21], a public EV recharging infrastructure [22] and a green taxation system that promotes the adoption of EVs [23].

This article explores some research prospects that arose in Ref. [1]. In particular, a smart charging strategy is tested, which requires detailed modeling of mobility. This approach enables reaching the CO_2 targets for 2050 with virtually no excess of energy. Furthermore, the extent to which PV energy can further transport electrification integration, and vice-versa, is explored in detail: the required penetration of one technology to enable the deployment of the other is determined quantitatively. To avoid repetitions, in this paper details are provided just for the new parts of the work.

2. Smart charging of electric vehicles

As detailed in Ref. [24], there are two main strategies for EV charging: (1) un-coordinated charging, in which the EVs start charging as they park, leading to potential critical impacts on the grid; (2) coordinated charging, in which charging is at a convenient time, such as during off-peak hours. It can be based on a simple set of rules, such as delayed charging (i.e., pre-programed charging), or it can be smart charging, i.e., an optimized charging under the command of an operator, based on price, load or regulation [25]. A delayed type EV charging, programmed for certain times of the day, was tested in Ref. [1]; this paper focuses on the smart charging strategy, which relies on the smart grid technology. As defined in Ref. [26], a smart grid is an electricity network that efficiently delivers sustainable, economic and secure electricity supplies integrating intelligently the actions of all users connected to it — generators, consumers and those that do both. It is based on a combination of hardware, management and reporting software built atop a communications infrastructure, constituting a great sophisticated and intricate network. At the moment it is on early stages. For an inventory of the smart grid research, development and demonstration projects in Europe, see Ref. [27].

In this context, the EV batteries may act as a form of distributed controllable energy storage and possible supply of power. This is the concept of vehicle-to-grid (V2G). Since EVs are parked more than 90% of the time [28], they offer the possibility for demand side response (DSM), namely load shifting. Conceptually, they can be seen as a nation sized battery [29]: (1) they can charge when it is more convenient for the system operator (SO), substituting large-scale energy storage systems (namely hydro-pump); (2) optionally, they can supply electricity (battery-to-grid) and ancillary services to the power system.[8] V2G implies: (1) a smart connection to the grid[9]; (2) a control device communicating with the SO and following its signals; (3) an on-board meter device.

The V2G concept was already approached in 1997 by Kempton and Letendre [30]. Since then, V2G was amply addressed in the literature, such as in Ref. [28], discussing the integration of wind energy into the transport and electricity sectors, and in Ref. [31], addressing the integration of large distributed PV penetration through EVs. Experimentally, V2G was tested in pilot projects, such as [32]. For a comprehensive review on the topic, focused on V2G and RES integration, see Mwasilu et al. [33]. For a review of smart charging approaches, see García-Villalobos [34].

Fig. 1 schematically represents the smart grid scheme with V2G functionality operating under the virtual power plant (VPP)[10] approach. The VPP control center dispatches the aggregated battery power whenever requested by the Distribution SO (DSO) and Transmission SO (TSO) and centralizes the energy and communication flow management between energy market players (i.e., producers and consumers) and the operators.

The provision of V2G services to the SO is ultimately determined by its profitability for the parts. The power markets where V2G could be integrated are: (1) base load, i.e., power generation paid on an energy basis that is running most of the time at low cost to cover for constant demand. V2G is not suitable for this market because cannot be price competitive due to EV limited energy storage, limited battery lifespan and high energy cost; (2) peak power, i.e., power generated during times of predictable higher demand, e.g. cold periods, paid also on an energy basis. Normally, it is provided by combined cycle gas turbine (CCGT) power plants, which can be switched on for short periods of time. This energy is relatively expensive, making in some cases V2G competitive for peak power.

[6] Electrochemical batteries are the most common option for current EVs [71].

[7] However, Portugal did not do yet the leap in order to start exploring its solar potential, having just 282 MW of solar photovoltaic installed [72]. As a comparison, despite of Germany having only 1200 kWh/m^2/year of solar resource available and Portugal 1900 kWh/m^2/year [73], the former has 438 W/person of solar PV installed against 28.2 W/person in the latter [74]. The reasons for this have a great amount of deal to do with a still lack of competitiveness in the price of the solar PV unit of energy when compared to other electricity sources, but that is changing. Competitiveness is assessed by grid parity: PV will reach it when the electricity produced by a PV system throughout its lifetime is at least as profitable as buying electricity from the grid [7]. Grid parity has already been partially reached in Spain, Germany and Italy [69] and due to the declining PV levelized cost of energy it is expected that the same happens gradually in the rest of the European countries [70].

[8] EVs could charge during off-peak hours, when the price of electricity is low, and sell to the electric companies under contract payments during those periods and, thus, more expensive, representing a profit for the EV owner. If this payment is lower than the cost of centralized power generation, the electric power companies will also realize profits [62].

[9] It should be noted that, in our meaning, V2G concept does not imply necessarily electricity flow from the batteries to the grid.

[10] Virtual power plant is defined as an aggregation of different type of distributed resources which may be dispersed in different points of medium voltage distribution network. It can be used to make contracts in the wholesale market and to offer services to the system operator [75].