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# Smart charging of electric vehicles with photovoltaic power and vehicle-to-grid technology in a microgrid; a case study

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## HIGHLIGHTS

- Simulation of microgrid including solar panels, electric vehicles and load demand.
- Comparison of smart EV charging control algorithms.
- Analysis of impact smart charging and V2G on PV self-consumption and peak reduction.
- Analysis of impact control algorithms on EV battery lifetime.
- Analysis of impact different microgrid configurations.

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## ABSTRACT

We present a model developed to study the increase of self-consumption of photovoltaic (PV) power by smart charging of electric vehicles (EVs) and vehicle-to-grid (V2G) technology. Whereas previous studies mostly use large EV fleets in their models, our focus is on a smaller scale. We apply the model to a microgrid in Lombok, a residential neighbourhood in the city of Utrecht, the Netherlands. The microgrid consists of a 31 kWp PV installation, an office, internet servers, three households, and two EVs. Three control algorithms are presented which manage the charging profile of multiple EVs either in real-time or using linear optimisation with predictions for PV power and electricity demand. We perform one-year simulations using data for PV power, EV use, and electricity demand. Simulations results are evaluated on PV self-consumption and peak demand reduction. In addition, we make qualitative statements on battery degradation resulting from the charging strategies based on several indicators. We also simulate changes in microgrid composition, for example by including more EVs. In the simulations, self-consumption increases from 49% to 62–87% and demand peaks decrease by 27–67%. These results clearly demonstrate the benefits of smart charging EVs with PV power. Furthermore, our results give insight into the effect of different charging strategies and microgrid compositions.



## 1. Introduction

The transition to low carbon energy and transport systems requires not only the large-scale adoption of clean technologies and efficiency measures, but also new energy management strategies to efficiently incorporate these innovations in the existing infrastructure. Issues related to the grid integration of clean technologies can occur both at the energy supply side, with technologies such as photovoltaics (PV), and on the demand side, with technologies such as electric vehicles (EV). Sophisticated energy management can help solving these issues and optimise allocation of resources, for instance by charging EVs with PV power instead of electricity from coal or gas-fired power plants.

In the residential sector, there is an imbalance between PV power supply and electricity demand. PV installations produce most electricity during the day [1,2], while electricity demand of households peaks in the morning and evening. Furthermore, typical EV charging patterns contribute to existing peaks in household electricity demand[1]. A higher penetration level of PV and EVs will increase power transport over the electricity grid, requiring grid investments to prevent overloads [3,4]. Several countries in Europe have started implementing policies to stimulate the

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[1] E-laad [Internet]. Opladen elektrische auto's zorgt voor piekbelastingen [update 2013 May 6th; cited 2014 May 14th] Available from: <http://www.e-laad.nl/nieuws/opladen-elektrische-autos-zorgt-voor-piekbelastingen-2/>. In Dutch.

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self-consumption of locally generated energy [5]. Self-consumption of PV power should increase to ensure grid stability and functioning.

In a smart grid the traditional electricity grid or microgrid (i.e. a local, low-voltage distribution system) is combined with information and communication technologies [6]. Load shifting is an essential aspect of smart grids and can be used to increase self-consumption of PV power [7] and off-peak charging of EVs [8]. An important advantage of EVs in smart grids is that they can be used both as a flexible demand source and as a storage option, using vehicle-to-grid (V2G) technology [9–13].

In this paper we use a case study to model and simulate the application of smart charging algorithms for EVs. Simulation studies on using EVs for integration of PV in the grid mostly use a high level of aggregation of EVs in their models. For example, two studies have been found that consider the case of using parking lots to integrate EV and PV. Tulpule et al. [14] have performed a study for a parking lot at a workplace in Columbus, OH, USA and Los Angeles, CA, USA and show the feasibility of such a system as compared to home charging both in terms of costs and $CO_2$ emissions. Birnie [15] considered a parking lot in New Jersey, NJ, USA and used a simple approach to determine that most driving needs could be met by solar power in the summer, but not in the winter. Other studies consider EV fleets at a city or region level. For instance, Zhang et al. [16] show that by using smart charging one million EVs combined with one million heat pumps can reduce excess PV power by 3 TW h for the Kansai Area, Japan. Drude et al. [17] study PV and V2G strategies in urban regions in Brazil. They conclude the EVs can be used for grid-stabilisation, but that adequate energy policies are needed to avoid destabilisation due to too many cars offering storage for V2G. Tuffner et al. [18] simulated a distribution system (IEEE 123-node) for Phoenix, AZ, USA weather conditions. They conclude that penetration rates of EV and PV have to be high (>50%) to have a significant impact on the network but that the synergy of these technologies has significant benefits for these high penetration rates.

According to Guille and Gross [19], EV batteries are too small to make a significant impact on the grid by themselves. However, large-scale deployment of V2G faces many socio-technical barriers [20]. Our study aims to show the benefits of using EVs and smart grid technology in a microgrid, since such a small-scale project can be realised in the near future. These innovative pilot projects are pivotal in realising the transformation of socio-technical systems such as the energy system as they allow the small-scale experimentation with alternatives to the current system [21–23]. Furthermore, studying this project allows us to combine specific real-world empirical data on PV power supply, load demand and EV use. This paper thus contributes to the existing literature by exploring alternatives to large-scale deployment of using EVs for integration of PV in the electricity grid.

Our case study is LomboXnet[2], a company providing internet connection to about 2500 people in Lombok, a neighbourhood in Utrecht, the Netherlands. LomboXnet has the ambition to run its activities on locally produced solar power and provides PV power to three houses in the neighbourhood. The company has two battery EVs, which are used for car sharing. Car sharing is becoming increasingly popular worldwide [24] and also in the Netherlands[3] and it has a great potential to reduce the environmental impact of personal transportation [25–27]. When used for car sharing, the EVs are regularly stationed at the charging station, making them suitable for grid balancing. This in contrast to other types of EV use such as commuting. The combination of PV, EV, smart grid and car sharing makes LomboXnet an excellent case for studying the integration of clean technologies.

Our research objective is to determine the potential for increasing the self-consumption of PV power with smart charging of EVs for LomboXnet. We simulate three different charging algorithms. The first algorithm uses real-time information, the second uses real-time information and V2G, and the third is an optimisation algorithm using predictions for PV power supply and load demand and V2G.

The remainder of this paper is organised as follows. In Section 2 we introduce our model. Section 3 presents our control algorithms and Section 4 the indicators used. Section 5 contains simulation results. In Section 6 we discuss our method and results and in Section 7 we draw our final conclusions.

## 2. Model description

In this section we present the structure and components of our model. Fig. 1 presents an overview of the microgrid of LomboXnet. The five main components of the microgrid are the PV installations, the energy management system, the uncontrollable load, the controllable load, and the connection to the main grid. The uncontrollable load consists of the office building, the internet servers and three households, each with a distinctive type of load curve. The demand from the office building peaks during the day, the internet servers have a constant demand and household demand peaks during the morning and evening. The PV power is used to cover both the uncontrollable and the controllable load. In case of PV power shortage, electricity is drawn from the main grid. In case of excess PV power, electricity is fed back into the main grid.

### 2.1. PV

The PV installations provide electricity to the microgrid. In total, 31 kWp is installed with a solar energy yield of about 25 MW h per year and a performance ratio (PR) of 74% as measured for the year 2013. The PR is a measure for the overall losses of a PV system and is defined as the ratio of final energy yield of the PV system in kW h/kWp to a reference yield, which takes only solar irradiation into account [2]. In the Netherlands, the average PR is 78% [28]. The below average performance of the LomboXnet PV system is explained by the partial shading of several solar panels during the day. The PV power output is directly measured at the solar inverter and available with a resolution of an hour.

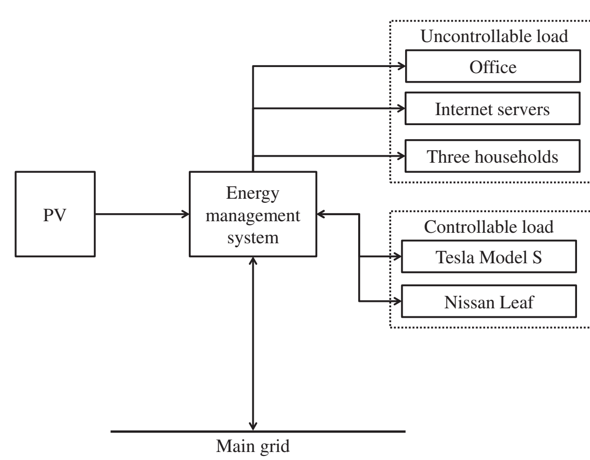


**Fig. 1.** Microgrid at LomboXnet, arrows indicate power flows.

[2] Company website available from: <http://www.lombox.nl>. In Dutch.
[3] KVPP [Internet]. Snelle opkomst onderling autodelen [update 2013 June 20th; cited 2014 September 5th] Available from: <http://kpvvdashboard-4.blogspot.nl/2013/06/snelle-opkomst-onderling-autodelen.html>. In Dutch.