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A price-responsive dispatching strategy for Vehicle-to-Grid: An economic evaluation applied to the case of Singapore

Dominik Pelzer [a,*,1], David Ciechanowicz [a,1], Heiko Aydt [a], Alois Knoll [b]

[a] TUM CREATE, 1 CREATE Way, Singapore 138602, Singapore
[b] Technische Universität München (TUM), Institute for Informatics VI, Robotics and Embedded Systems, Germany

HIGHLIGHTS

- A charging and dispatching strategy for optimizing profits from V2G is presented.
- This optimization strategy builds on temporally resolved electricity market data.
- A case study shows that this method turns a S$ 1000 annual loss into a S$ 130 profit.
- Sensitivity analyses indicate potential for further increase of profitability.
- Employing this strategy in other countries is assumed to yield much greater profits.

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ABSTRACT

Employing electric vehicles as short-term energy storage could improve power system stability and at the same time create a new income source for vehicle owners. In this paper, the economic viability of this concept referred to as *Vehicle-to-Grid* is investigated. For this purpose, a price-responsive charging and dispatching strategy built upon temporally resolved electricity market data is presented. This concept allows vehicle owners to maximize returns by restricting market participation to profitable time periods. As a case study, this strategy is then applied using the example of Singapore. It is shown that an annual loss of S$ 1000 resulting from a non-price-responsive strategy as employed in previous works can be turned into a S$ 130 profit by applying the price-responsive approach. In addition to this scenario, realistic mobility patterns which restrict the temporal availability of vehicles are considered. In this case, profits in the range of S$ 21–S$ 121 are achievable. Returns in this order of magnitude are not expected to make Vehicle-to-Grid a viable business case, sensitivity analyses, however, show that improved technical parameters could increase profitability. It is further assumed that employing the price-responsive strategy to other national markets may yield significantly greater returns.

1. Introduction

In a power system, electricity demand and supply are subject to continuous fluctuations which cause deviations from the desired voltage frequency. This requires an instantaneous intervention by the system operator which restores the equilibrium between power demand and supply. Power grid stability is either ensured by power plants which are able to quickly adjust their power output or by storage facilities which serve as buffers for energy excesses or shortages. Most of these solutions, however, are either costly or entail large space, presenting a need for developed concepts that offer greater economic advantages. This becomes especially vital with growing shares of intermittent renewable energies which will further increase the need for frequency regulation.

As part of a future smart grid, *electric vehicles* (EV) could play a major role for the fine-tuning of energy demand and supply. On average, a vehicle is parked 23 h a day [1]. During this time, its battery pack could be employed as a buffer for power excess or shortage by either charging the battery or by feeding electricity back to the grid. This concept termed *Vehicle-to-Grid* (V2G) was first mentioned in 1997 [2] and has been subject to intensive research in the last two decades. In this context, various theoretical investigations confirmed its effectiveness to improve power grid stability [1,3–7] and several fully functional prototypes where implemented [5,6,8].

For EV owners, V2G could create revenues that would accelerate the amortization of vehicle investment costs. Economic feasibility

* Corresponding author. Tel.: +65 6601 4015; fax: +65 6694 0062.
E-mail address: dominik.pelzer@tum-create.edu.sg (D. Pelzer).
[1] These authors contributed equally to this work.

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studies have been conducted for different countries which, depending on their assumptions, arrive at different conclusions on the profitability of V2G [1,7–12]. One major drawback of previous analyses is the use of static models that are built on average values of electricity market data [7,9–12]. Electricity prices, however, highly vary during the course of a day, presenting varying scenarios where V2G may yield profits in one time period but result in losses in a different one. These unprofitable periods were incorporated in previous studies which led to an underestimation of achievable profits. The ability to distinguish between profitable and unprofitable time intervals is therefore crucial for maximizing monetary returns. Furthermore, individual travel itineraries impose restrictions on the temporal availability of vehicles. Knowing whether a vehicle will be primarily available during profitable or unprofitable periods is therefore essential to deduce a reliable conclusion on possible profits.

This paper presents a method which builds upon temporarily resolved electricity market data. This allows the emulation of a smart charging/dispatching strategy which aims to maximize V2G profits by avoiding unprofitable time periods. This method furthermore permits investigations on the effects of different realistic mobility patterns which define the times EVs are grid-connected.

As an application of the price-responsive strategy, profits for various scenarios were calculated using the example of Singapore. The city state serves well as an application for the model because of several reasons: The electricity market structure is simple so that no simplifying assumptions need to be made. Furthermore, all required data are publicly available and finally, relevant prices are fairly low so that the outcome is expected to mark a lower bound for profits when compared to other countries.

The remainder of this paper is structured as follows: Section 2 briefly introduces the V2G concept. Section 3 discusses the electricity market in Singapore and sketches the available market data. In Section 4, the price-responsive cost-revenue model is introduced. In Section 5, this model is applied to several scenarios building on data for Singapore which leads to a conclusion on the conditions for the economic viability of V2G. The results are then further investigated in the sensitivity analysis in Section 6. In Sections 7 and 8 findings are discussed and an outlook on future research is given.

2. The V2G concept

The V2G concept is depicted in Fig. 1. Energy is produced in power plants and transmitted through maximum, high, medium and low voltage lines to the consumers (e.g. households, enterprises, charging stations, etc.). One type of consumers are EVs which may either use the energy for driving or serve as a short-term energy storage by charging their batteries in case of power excess or feeding electricity back into the grid in case of power shortages.

The amount of energy and power each individual EV can provide, however, is too low to participate on most electricity markets (in Singapore 1 MW for half an hour is necessary). Meeting these conditions thus requires hundreds to thousands of EVs aggregated to an *Electric Vehicle Virtual Power Plant* (EV-VPP) [5,13]. This is done by an aggregator who serves as a mediator between the EV owners and the electricity market. The aggregator trades energy at the market and ensures that the EV-VPP is capable of providing the contracted power at all times.

3. Electricity market in Singapore

In Singapore, energy is traded at the *National Electricity Market Singapore* (NEMS) which is controlled by the *Energy Market Authority* (EMA) [14]. Within the energy market, several sub-markets can be distinguished. To explain which of these markets are potentially relevant for V2G, they are briefly discussed in the following sections.

3.1. Base, central and peak load

Base load is defined as the lower bound of the daily energy demand. Energy for this load type is produced at the lowest possible production costs considering country-specific governance rules, e.g. regarding security, emissions, etc. Central and peak load constitute the fraction of energy demand which is variable but predictable with high accuracy. Energy for base load can be provided by any kind of power plant while the latter two load types require power generators which can efficiently adapt their output on a medium time scale.

In Singapore, 96% of electricity generation is provided by gas and oil power plants [15]. Their flexibility allows covering all three load types so that no distinction between base, central and peak load is made. In a result, there is only one price an entity has to pay when buying electricity from a generator, called the *Uniform Singapore Energy Price* (USEP).

As fluctuations of these load types are low and predictable, they can be efficiently balanced by conventional and inexpensive power

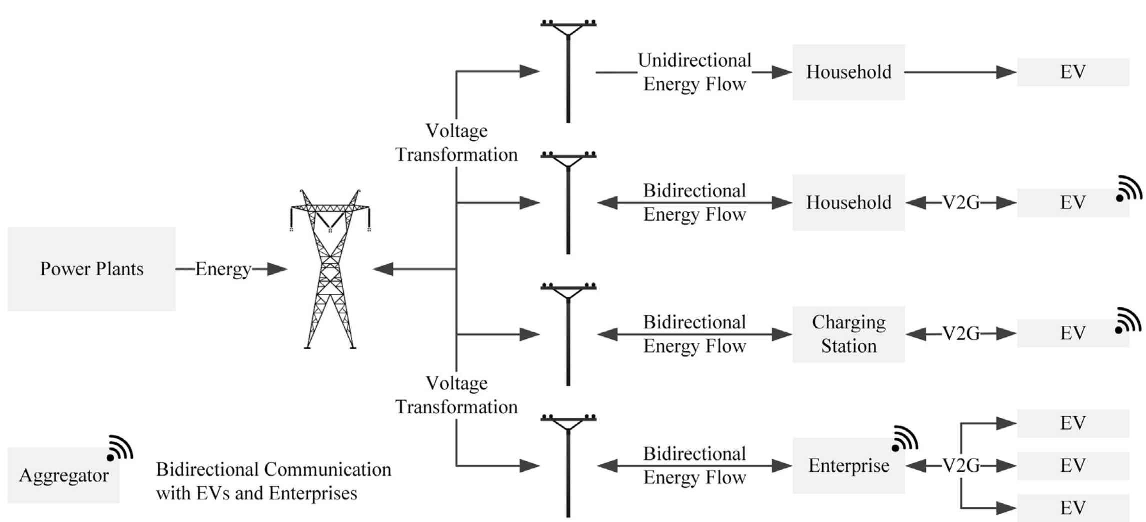

Fig. 1. The V2G concept: energy and communication flows. Adapted from Ref. [9].