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Integrated planning of low-voltage power grids and subsidies toward a distributed generation system – Case study of the diffusion of photovoltaics in a Japanese dormitory town

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A B S T R A C T

This study proposes a novel approach for a local society to design effective diffusion scenarios for distributed energy systems, namely, the integrated planning of two design problems: the design of low-voltage power grid systems and the design of subsidy systems for the introduction of photovoltaic systems. In particular, a household photovoltaic system is considered to be a distributed generation system. Integrated planning comprises (1) upgrading of power grids and the installation of the photovoltaic system supported, at least in part, by a local government, (2) controlling the timing of photovoltaics installation and the upgrading of the power grid section by section, and (3) increasing the distributed generation capacity in low-voltage grids by upgrading a pole transformer to an auto-adjusting transformer. This study focuses on a case study of rooftop photovoltaics in a Japanese town. The proposed concept is verified through a multi-agent simulation, which supports quantitative evaluation of the proposed plans. The input data of the simulation for the behaviors and interactions of stakeholders are obtained through a questionnaire survey. A voltage analysis of a power grid is included in the multi-agent simulation. The analyses reveal that integrating the two planning problems provides synergic effects toward advancing the diffusion of photovoltaic systems.

1. Introduction

Distributed generation (DG) systems are attracting substantial interest as a means to supplement or replace conventional, large-scale central power systems because of the potential for DG systems to reduce carbon emissions, increase energy savings, and ensure independent power generation in the event of a natural disaster [1]. Expectations for DG systems have grown particularly high in Japan since the Great East Japan Earthquake of March 11, 2011 [2]. Some examples of DG systems include cogeneration systems and renewable energy systems, such as solar photovoltaic panels (PV) and wind power generators.

When a typical household considers the installation of a DG device, their decision-making includes a wide range of value judgments, but from the viewpoint of encouraging the wider diffusion of DG devices, the most important factor is thought to be economics. The power generated by installed DG devices can help reduce electricity costs while also generating revenue by selling surplus power, and thereby recovering the initial investment cost. In recent years, the use of DG systems has been increasing, as a result of lower installation costs, government subsidies for renewable energy, and the introduction of the Feed-in Tariff (FIT) [3]. Under the FIT system, when a DG device is installed and connected to the power grid, the power company is obligated to purchase the power generated by the device at a comparatively high fixed price for a certain period after an application is made.

On the other hand, problems have been highlighted, including increased power generation costs and instability in power supply. One major issue is the voltage increase in the power grid, which raises the question of how DG systems can be integrated with the existing energy infrastructure. The structure of power grids consists of substations for power distribution, high-voltage lines, low-

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voltage lines, and end consumers. Residential buildings and domestic PV systems are connected to low-voltage systems. When a DG device is connected to the grid, the voltage at the points of connection increases in accordance with the power output, which fluctuates over time as the amount of solar radiation varies. This, in turn, affects the voltage distribution of the entire power grid. However, current power grids are not designed for connection with a large DG capacity. As such, there are fears that as more DG devices are connected to the grid in the future and fluctuations in voltage distribution increase, voltage values at some points in the power grid may fall outside the allowable range, making it necessary to shut down power to protect system [4]. The DG output would be restricted to the connectable capacity: any power in excess of this would not be practically usable. The excess power could not be sold. Such a situation would serve as a disincentive to the diffusion of DG devices.

There have also been a number of studies that have analyzed the impact that the diffusion of distributed power generation would have on power grids. One such study analyzed the effect that a significant increase in PV systems would have on the voltage along distribution lines in residential areas [5]. Some studies analyzed the costs of voltage variation caused by the wind speed variation for wind turbines [6] and solar irradiance variations for PVs [7]. A case study was also carried out to find the most effective penetration level of PV in a local low-voltage distribution grid [8]. The analysis approaches of these studies suggest a model for evaluating the DG capacity of a grid to find the optimal allocation of DG devices.

For excess power reduction and achieving grid compatibility of DG, a basic approach is to control the output of DG devices, e.g., solar inverters with reactive power control capability [9], fuzzy integral sliding mode current control strategy [10], and shunt active power filters [11]. Since the aim of such a basic approach is to stabilize the output, it is sometimes necessary to constrain power generation by DG. Demand response is another approach where consumer devices can be turned on to use excess power when it is available. While there has been work to assess the potential of this approach [12] and propose optimal electricity tariffs for it [13], such an approach requires dramatic changes in consumers' consciousness. As a promising countermeasure against the voltage increase problem, the introduction of battery storage has been shown to be effective for low-voltage grid management [14]. Batteries are the most commonly used and well-suited storage technology for small, distributed solar PV applications and wind turbines [15]. Recently, the impact of linking electric vehicle (EV) storage batteries to power grids has been discussed with respect to this issue [16], because of their increasing diffusion. Several studies on the EV approach have been carried out, including an analysis of multiple scenarios by varying the timing of EV recharging and comparing the annual cost of electricity between cases [17], an assessment of the effect of the installation of battery storage systems in households to increase the self-consumption of PV-generated power [18], and an assessment of net present value of EV and stationary battery storage with a techno-economic optimization model of a household system [19]. In reality, however, battery storage systems are not yet widely used, because these systems are not cost-competitive [20], have safety problems, and their long-term reliability has not been validated [21]. Therefore, battery storage systems are not yet suitable for installation on a large scale, although they are feasible for use in small areas or public facilities.

Transmission capacity expansion is another promising countermeasure for the voltage increase problem and aims at smoothing the voltage variation by connecting distributed grid networks [22]. It can potentially reduce distribution losses [23]. Low-voltage transformers installed at points at which a low-voltage bus branches from a high-voltage bus also play an important role. Parameters related to transformers, such as their number, rated power, and maximum strait-line distance to each transformer, impact the capacity of a low-voltage grid [24]. An auto-adjusting transformer (AAT) is a feasible and effective measure for increasing DG capacity, because it enables the automatic control of the voltage in a grid by a controllable tap changer [25].

Any measure applied to a low-voltage power grid should be applied in conjunction with the installation of DG devices to avoid installation cost increases. Therefore, this study proposes a novel approach for a local community to effectively design DG systems, through the integrated planning of subsidy policies and the power grid, which were previously conceived and implemented separately. In particular, as an effective measure for increasing the DG capacity, the present study considers the AAT and a household PV system as the DG device. Through quantitatively evaluating the proposed plans, the present study attempts to identify the most promising plan. For the design and evaluation of the proposed plans, this study constructs mathematical models of the interdependent relationships among the power grid, subsidy policies, general households, and other boundary conditions, which are the main considerations in the adoption of a DG system. This process adopts multi-agent simulation (MAS), a promising technique for handling co-creation, based on a new trend in system design known as the "co-creative approach". This study considers a case study on the use of PVs for a DG system in the Mishima area of Osaka Prefecture, Japan (Suita City, Settsu City, Ibaraki City, Takatsuki City, and Shimamoto Town in Mishima County). This study conducts a questionnaire survey to gauge trends in the diffusion of and consumer interest in PV systems in the target area. Scenarios of plans are designed based on the survey results, and these scenarios are evaluated by applying the values of various parameters extracted from the survey results to the MAS model. The effectiveness and feasibility of the plans for connecting DG to existing power grids are examined based on these scenarios.

As stated above, many studies have been carried out on voltage increases caused by DG. The novelty of this study can be summarized by the following three points. First, this study proposes a novel concept for integrated planning of a power grid and a subsidy which a local government can implement. It introduces a concept called sectioned aid for introducing DG and grid upgrading in order to control the timing of both. Second, this study proposes a methodology for solving the integrated planning problem based on an MAS model. Third, a case study of one area in Japan is carried out based on a questionnaire survey of 1200 households. Parameter values obtained through the survey are used to set the MAS parameters. Some new technologies for enhancing PV efficiency are now available, such as hybrid photovoltaic thermal (PVT) systems. However, since this study intends to focus on an approach for handling complicated interactions among stakeholders, it is sufficient to consider only simple PV systems.

The remainder of the present paper is organized as follows. Section 2 explains our methodology and presents planning based on MAS, which is our approach for tackling the complex problem posed by integrated planning. First, Section 2.1 defines the fundamental concepts of integrated planning. This is followed by the definition of the planning problem (Section 2.2), the construction of mathematical models (Section 2.3 and Appendix), and the definition of the planning process (Section 2.4). Section 3 presents the results of a case study of the Mishima area. It begins with an analysis of the features of the Mishima area (Section 3.1). Based on the analysis, a questionnaire survey is conducted of inhabitants in the area (Section 3.2). Candidate scenarios of integrated plans are also created (Section 3.3). An MAS is created by incorporating the questionnaire survey results into the mathematical model in Section 2.3 (Section 3.4). Candidate scenarios are then evaluated