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# Agent-based simulations of the influence of social policy and neighboring communication on the adoption of grid-connected photovoltaics

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ABSTRACT

Agent-based simulations coupled with an analysis of the flow of electric power are carried out to examine the influence of the social policy of the government and the neighboring communication between customers on the adoption of distributed rooftop photovoltaic electrical power generators (PVs). How the relationships between the social policy and the possibility of a reverse current restriction give rise to the collective behavior of autonomous individuals, and how the end customers interact and form relationships with its environment are described. Strong intervention by the government in the areas near a main high-voltage power distribution transformer, where the possibility of a reverse current restriction is relatively low, drives the greatest adoption of the PV system. The near areas are primarily occupied by customers with only a PV to improve the diffusion rate of PVs via the self-organization by the communication between customers. It also lead in a decrease in the need for compensation devices, which in turn minimizes the social cost. Growth in the number of PVs in areas far from the transformer is assisted by the installation of batteries as compensation for the lost opportunity due to restrictions in those areas on reverse power currents. Therefore, excessive intervention by the government in the far areas results in an increase in the social cost of managing reverse currents.

## 1. Introduction

Integration of distributed power sources, as related to dispersed generation technology and environmental engineering and including renewable energy sources, e.g., rooftop photovoltaics (PVs) in power networks, is an emerging area of research in electrical engineering [1,2]. The imbalance between an individual customer's electrical power demand and the power supply from a PV is one of the problems of integrating PVs into power networks. Customers who have installed a PV are willing to return that excess power to the network, which results in the increase in the local voltage in the power line. Selling of excess power results in a current that is the reverse of the original distribution current; as a result, the local voltage in the power line increases. When the local power distribution line voltage exceeds an acceptable limit of 107 V [the standard voltage of 101 ± 6 V is stipulated in the electric utility industry law (Electricity Business Act) in Japan], the customer cannot return excess power to the network, referred to as a restriction on the reverse current or as an output restriction [3–5]. This restriction may well be one of the most serious issues for progress in the adoption of the installation of PVs. In order to overcome such issues, it is important to consider not only the electrical engineering aspect, i.e., technologies related to distributed power sources or power networks [6–9] but also the social science aspect, i.e., human behavior, economical or regional aspects [10–14].

As an original objective, we have developed a hybrid approach, combining electrical engineering (electric power load flow analyses) with a social science approach (agent-based modeling of society) to predict the influence of neighboring communication and social policy on the rate of diffusion in a society of distributed PVs [15]. Recently, agent-based modeling, e.g., multi-agent systems [16,17], has been widely used in the subfields of energy engineering, i.e., communication and marketing [18–27] and power system engineering and managements [28–44]. The benefit of the multi-agent systems [28,29] has been investigated for the state estimation [30] and efficiency evaluation [31] of networks, the control and optimization of power flow [32–37], and power system restoration [38–41]. Furthermore, some studies have examined the energy management of a hybrid system with renewable energy sources [42–44]. In contrast to those studies focusing on electrical engineering aspects, the highlight of this work is to achieve a fusion between engineering and sociology.

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The direct intervention via official campaigns of PV promotion by the government is important for the adoption of the PV system. However, the relationship between the geometrical distribution of the probability of output restriction and the strength of the social policy, and the related transient dynamics and growth of the integrated society have not been fully understood. The purpose of present paper is to identify how the relationships between the social policy and the possibility of a reverse current restriction give rise to the collective behavior of autonomous individuals, and how the end customers interacts and forms relationships with its environment.

## 2. Modeling

A conceptual diagram of our hybrid model is shown in Fig. 1. At the city and community scales (lower region), the power flow is analyzed for the high- and low-voltage distribution networks and a few thousand grid-connected homes. In the multi-agent system (upper region), the individual customer's *intent or choice* is formalized. Each of the thousands of customer agents make their own individual-scale decision to purchase, install, and operate a PV and/or a compensation device. They are influenced by both neighboring communication and PV promotion by government. The customer agents live their own lives in the two-dimensional artificial society (middle plane). Consequently, the society can reach a compromise (which might not be the best solution, but will be one based on reasonable agreement). We can observe the transient dynamics, the growth of the integrated society, and the influence of local communication and global government intervention on the adoption of PVs.

### 2.1. Electric power load flow analysis

The behavior of a 6.75 kV-class power network is simulated for a two-dimensional $50 \times 50$ grid with 2500 end customers (the grid squares). The network consists of a main high-voltage power-distribution line (a main high-voltage power transformer is located at $(x, y) = (0, 25)$), 250 middle-sized pole-mounted transformers with low-voltage service lines, and 2500 grid-connected end customers. The distance between the branch points, i.e., the pole-mounted transformers, is fixed at 50 m. Ten customers (5 customers × 2) are connected via service lines to each middle-sized transformer. The three-phase three-wire distribution system for the high-voltage line is treated as a three-phase balanced load in the flow calculation, and a single-phase (100 V) load is balanced on a single-phase three-wire distribution system for the low-voltage line.

A load flow analysis determines the probability of a reverse current due to a PV at each of the grid points (customer agents). We simulated an extreme situation with a PV diffusion rate of 100% where the power generated by a PV could be returned to the network without any restriction. The line voltage increases from the rated value of 6750 V at 0 m along with the distance from the main power distribution transformer. The reverse current is restricted when the voltage exceeds 6837 V at 450 m. Therefore, customers far ($\geqslant 450$ m) from the main transformer cannot sell the excess power generated by their PVs. The probability of restriction clearly depends on the distance between the main power distribution transformer and the end customers.

Discontent with a restriction on output results in motivation to install a compensation device. Our model takes into account neither tap-changing controls in transformers nor reactive controls by PV power conditioners [5,6], i.e., the voltage in the transformers is fixed, and the power factor in the PV system is constant. We assume that the battery storage system is provided by the government free of charge as compensation for the lost opportunity caused by the restrictions on output, with particular emphasis on the scenario that the supply of the battery system in turn results in an increase in social cost that is sustained by taxes.

Table 1 shows the calculation conditions of the power load flow analysis. For details of the power flow analysis see [15].

### 2.2. Multi-agent system

The multi-agent system includes two types of agent, i.e., customer agents (at each of the grid points) and the government agent. Fig. 2 shows a schematic of the state ($S$) and the state-transition ($T$) of

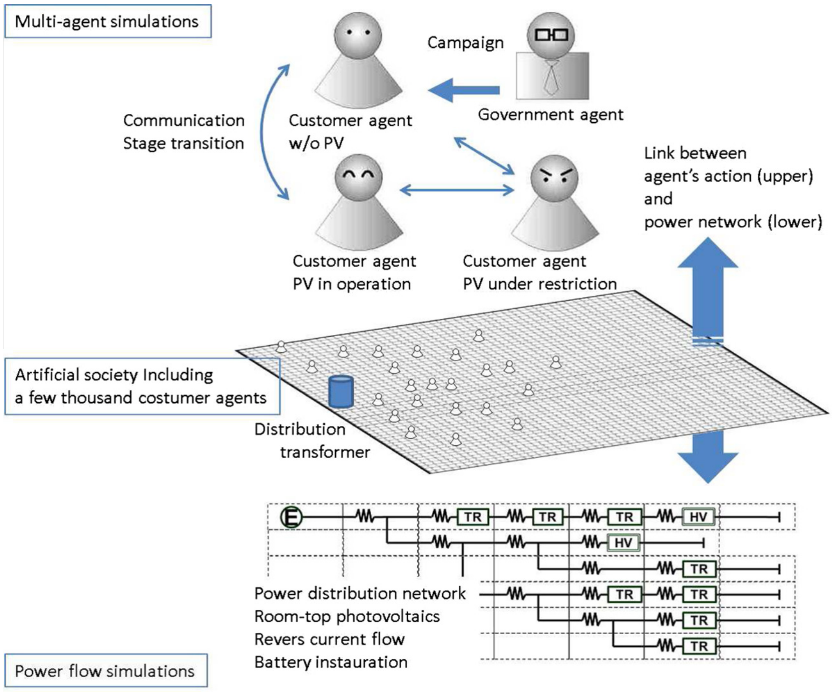

**Fig. 1.** Conceptual diagram of the present hybrid model; power flow analysis (lower), multi-agent simulation (upper), and a two-dimensional artificial society (middle plane).