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ScienceDirect

Energy Procedia 105 (2017) 3269 – 3274

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Spatially-Explicit Resilience Modeling for PV Electricity Supply-Demand Balance

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Abstract

We analyse the potential of PV (Photovoltaic) in terms of electricity resiliency by developing a spatially-explicit model for the PV supply and household demand balance. The model estimation is conducted using hourly solar irradiance data for a whole year for the Tokyo metropolitan area. We have tested the resiliency of the bland against several scenarios of climate uncertainties. Our analysis shows that, although PV supply for the whole Tokyo is smaller than household electricity demand, high level of electricity surplus exists in the western central area where the disaster risk is relatively low, while, few electricity surplus remains in the eastern high disaster risk areas. These results suggest that if we are to create community- based regional resilient electricity sharing grid system ([1]) in the future, we need to create additionally a city scale multi-layer electricity sharing system for adjusting the dynamics demand-supply discrepancies by transferring PV surplus electricity to the high risk areas.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: Photovoltaic; disaster risk; surplus electricity; resilience; Tokyo metropolitan area

1. Introduction

In Japan, PV generation systems are rapidly spreading because of the following reasons: (i) the Feed-in-Tariff scheme was implemented in 2012 to offer an agreement for purchase of sustainable energy; (ii) the PV generating cost is rapidly declining [2]; (iii) PV generation, which is a decentralized system, is resilient against disaster risks rather than typical centralized generation systems. The last point is especially important in Japan, where the disaster risks are gradually increasing under the climate change. Especially, disaster risk in the Tokyo metropolitan area is estimated the highest among world major cities

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Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.734

by [3]. Increasing energy resilience utilizing PV and other sustainable energies is an emerging task in the Tokyo metropolitan area.

A number of PV-based systems for sustainable development, such as the vehicle-to-community system ([4-6]), has been studied and planned in some model cities (see, [2]). Yet, it is less clear whether PV can provide a sufficient amount of electricity. Although [3, 6] estimated PV supply, they used solar irradiance data in each month, and did not consider daily. Also, they did not explicitly consider the spatial variation of solar irradiance. Besides, they did not consider actual temperatures that change efficiency of PV generation. Fortunately, a dataset including hourly solar irradiances and temperatures in each day is recently published (METPV-11: [7]; see, section 2).

The objective of this study is analyzing the potential of PV in terms of electricity resiliency by developing a spatially-explicit model for the PV supply and household demand balance. The potential is measured by 1 km grids using surplus electricity (see, section 2.1). The target area is the Tokyo metropolitan area.

2. Estimation approach

2.1. Surplus PV electricity

Surplus PV electricity is evaluated using Eq.(1):

$$S_{i,d} = \sum_{h} PV_{i,h,d} - \sum_{h} D_{i,h,d} \tag{1}$$

where i is an index of 1 km grids, $d \in \{1,...365\}$ is an index of dates, and $h \in \{1,...24\}$ is an index of hours. $PV_{i,h,d}$ and $D_{i,h,d}$ are PV supply and electricity demand, respectively, and $S_{i,d}$ is the surplus electricity in i-th grid in d-th day. PV supply is evaluated under three scenarios, which are explained just below (scenario changes coefficients on PV).

2.2. PV supply

The PV supply is evaluated by Eq.(2):

$$PV_{i,h,d} = I_{i,h,d} \times \tau \times roof_i^{PV} \times \eta \times K(T_{i,h,d}) \times p \tag{2}$$

where $I_{i,h,d}$ is the solar irradiance, τ is the array conversion efficiency (= 0.1), η is the efficiency of power conditioner (= 0.95), and p is the performance ratio (=0.89). $K(T_{i,h,d})$ is the temperature correction coefficient depending on the hourly temperature, $T_{i,h,d}$. Based on [7], the function is given by $1 - 0.04 \times (T_{i,h,d} - 25)/25$. $roof_i^{PV}$ is the PV installation area. We assume $roof_i^{PV} = A_i \times 1/\cos \psi$, where A_i is the building area in grid i (source: Fixed property tax cadastre), and ψ is the optimal angle of inclination (= 30 °). Note that this assumption implies that we assume a situation that PV panels are installs on rooftops of all detached houses (see, [4]). In other words, we quantify the maximum potential of PV generation under three solar irradiance scenarios (see, below).

Data of solar irradiance, $I_{i,h,d}$, are not available at 1 km grid level. Hence, we estimate it using the METPV-11 database (source: New Energy and Industrial Technology Development Organization). This database includes hourly irradiation data at 116 monitoring stations under maximum, minimum, and medium radiation scenarios. The maximum-scenario data is constructed as follows: (a) January whose irradiation was the strongest is selected between 1990 and 2009; (b) the other 11 months whose radiations are the strongest are selected just like (a), respectively; (c) hourly irradiation data in the selected 12