Renewable and Sustainable Energy Reviews 91 (2018) 1019–1024

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Estimating the effect of module failures on the gross generation of a photovoltaic system using agent-based modeling

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ARTICLE INFO

Keywords:
Photovoltaic
Maintenance
Agent-based model
Module failure

ABSTRACT

Photovoltaic modules represent the largest single investment in most photovoltaic systems. Ensuring that photovoltaic modules are functioning as intended is key to achieve its designed voltage and current output. Unfortunately, photovoltaic modules fail occasionally and a single failed photovoltaic module, which can go unnoticed for substantial periods of time, causes all power output for the sting it is included in to cease. The effect of these module failures on the total electricity generation of a photovoltaic system during its life cycle has not yet been adequately explored. The objective of this paper is to investigate how much the gross generation of a photovoltaic system is reduced due to module failures over the course of its life cycle. To investigate this effect, an agent-based model is developed to simulate the module failures in a 3,229-kW rooftop photovoltaic system located in Daejeon, South Korea. Through simulation it was found that if routine maintenance cycles are shortened from 52 weeks to two weeks, the system generates an additional 430 MWh over its life cycle. These findings can be integrated into strategic module replacement schemes by enabling photovoltaic system owners to make more precise system valuations. Further, the findings provide a basis for determining optimal routine maintenance schedules for various maintenance costs scenarios.

1. Introduction

Photovoltaic (PV) systems generate electricity directly from sunlight using solar cells (also called PV cells). Solar cells are a semiconductor device that converts solar energy into direct current (DC) through the PV effect [1]. Multiple solar cells that are electrically connected are called a PV module (also called a PV panel); a series of wired PV modules is referred to as a string. Strings are then grouped together to form a PV array and are used to produce the desired voltage and current outputs of a PV system. Within a PV system when a solar cell fails, it is not possible to repair the individual cell because it is encapsulated within the PV module [2]. Consequently, it only takes a single solar cell to malfunction for a module fail. To repair the system, the PV module housing the failed cell must be replaced. As such, PV modules are the most basic and main component of a PV system.

Since PV modules are the building blocks of a PV system, it is essential to ensure that PV modules are functioning as intended to achieve designed voltage and current outputs [3–5]. Failed PV modules are replaced through reactive maintenance. In other words, most defective PV modules are only found during routine maintenance. Once identified as failed, the entire module is replaced. Here, PV module failures are defined as an overall reduction in the power of a PV module. These failures range from degradation of performance, which involves a gradual reduction in power over time, to complete failure. One of the major concerns regarding failed PV modules is that they can go unnoticed for a significant period of time (e.g., six months, a year). If a PV module fails shortly after its annual routine maintenance, the failed module will likely remain in place until the following year.

Unfortunately, to the best of the authors' knowledge to date, the limited research on failures of PV modules have focused exclusively on PV modules themselves (e.g., the power reduction from a single PV module when it fails, causes of failures of PV modules, methods to identify failed PV modules). The effect of PV module failures on the gross generation of whole PV systems have not been adequately explored. Orkisz [6] estimated the effect of individual PV module failures on PV array output at a specific point of time but did not account for system degradation over time. This is an important caveat because, as PV systems age, module performance slowly deteriorates. Consequently, when failed modules are replaced with new units, the efficiency of the system increases. Accounting for fluctuations in system efficiency would yield more accurate estimates of the effect of PV module failures on gross generation over a PV system's life cycle.

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https://doi.org/10.1016/j.rser.2018.04.054
Received 27 June 2017; Received in revised form 7 February 2018; Accepted 14 April 2018
1364-0321/

Considering that failed modules incapacitate the entire string in which it is included and that failed units can go undetected for substantial periods of time, the impact of the module failures on gross generation requires investigation. To make more precise system valuations, the effect of module failures on the gross generation of a PV system over its life cycle needs to be better understood.

The objective of this study is therefore to estimate the effect of PV module failures on the gross electrical output of a PV system during its life cycle. In order to achieve this, an agent-based model is developed to simulate this effect. Agent-based modeling is a computational method to create, analyze, and experiment with models comprised of heterogeneous agents interacting each other within an environment [7,8]. Agent-based modeling is appropriate to simulate PV systems and modules (i.e., basic building block of a PV system) for several reasons. First, the components of PV systems can be thought of as heterogeneous agents, each with its own state (e.g., normal or failure, level of degradation). Second, agent-based modeling's bottom-up modeling methodology permits the flow of electricity down the hierarchical structure of a PV system (i.e., modules-strings-arrays-system) to be accurately represented. Findings from this study will aid PV system owners in determining routine maintenance cycles for various maintenance costs by enabling them to make more precise system valuations. The structure of this paper is as follows. This paper proceeds with a review of the literature on PV module construction and failures. Next, an agent-based model is developed to estimate the amount of loss due to PV module failures over a system's life cycle. Finally, this paper is concluded with a discussion of routine maintenance policies to reduce the loss of the gross generation due to PV module failures.

2. Literature review

2.1. PV module structure

A set of electrically connected solar cells is encapsulated into a single and long-lasting unit, which is called a PV module. This encapsulation structure enables PV modules to withstand adverse weather conditions (e.g., rain, snow load, cycles of heat and cold). Various different types of PV modules exist, and the module structure is different for different types of solar cells (e.g., crystalline silicon solar cell, thin-film solar cell).

A typical solar cell produces 0.6 V. Since half a volt is too low to use in most desire applications, solar cells are connected in series to generate higher voltages, this is known as stringing. Generally, a PV module is composed of two to four internal strings of solar cells. For the remainder of this paper, unless otherwise noted, a PV module refers to a crystalline PV module, as it is the most common type of PV module in use.

Within a PV module, usually located in the module's junction box, a couple of bypass diodes are inserted to prevent mismatch effects which can create reductions in power output [9]. Typically, a bypass diode protects 15–20 solar cells (i.e., a single internal string) from mismatch losses. If only one solar cell within a module with three bypass diodes (i.e., three internal strings) fails, the module would lose one third of its generating capacity. If no bypass diodes were in place, the module would lose all of its generating capacity. Even though bypass diodes allow current flow to bypass internal strings that cannot produce sufficient current, a PV module with two-third of its original output power represents a significant reduction in output. Since PV modules are connected in series (i.e., string) to increase the voltage of a PV system, the reduction in the output of a single PV module can lead to a loss at the whole string including it [6]. Therefore, PV module failures can result in considerable losses of gross generation even if the average annual failure rate for PV modules is as low as one percent.

2.2. PV module degradation and failure

PV modules represent the largest single investment in most PV systems. Each PV module is rated by its manufacturer for output power, watt-peak (Wp), at standard test conditions. However, PV modules nearly always produce less than their rated peak power in real-world conditions [10]. Module efficiency decreases over time due to solar cell degradation and failure [11]. Generally, manufacturers guarantee that their PV modules' efficiency will be over 90% of the rated peak power for 10 years and over 80% for 25 years. According to a study of 2128 PV systems [12], the median and mean degradation rates for PV modules were 0.5% and 0.8% per year, respectively. Rates of degradation varied slightly by PV technology type (e.g., amorphous silicon, cadmium telluride, copper indium gallium selenide, monocrystalline silicon, multicrystalline silicon, thin-film) and manufacturing date (e.g., pre-2000, post-2000) [13–22].

In addition to annual performance degradation, modules can also fail. PV modules fail for a wide variety of reasons. The predominant failure modes of PV modules are delamination, back sheet adhesion loss, junction box failure, and frame breakage [23–25]. These failure modes occur in nearly all PV module types. Silicon wafer-based PV modules are also subject to ethylene vinyl acetate discoloration, cell cracks, snail tracks, burn marks, and defective bypass diodes [26,27]. Since the output power of a PV module is proportional to the amount of irradiance that strikes each of the solar cells, dirt/soiling on the surface can severely affect electrical output [28].

PV module failures can be discovered by noticing reductions in output on the terminals of the PV modules. Drops in output are proportional to the number of the solar cells in the faulty internal string. Thermal infrared cameras are useful in diagnosing PV module failures as they can be used to inspect installed PV modules during normal operation. Visually inspecting modules is the most effective and quickest method to identify dirt/soiling. However, regardless of inspection method, it is time-consuming to inspect numerous PV modules one by one. Due to the considerable time requirements for inspection, large systems tend to have longer maintenance cycles. Thus, failed modules often go unnoticed for longer periods of time in large systems.

Various field and review studies have been conducted on the failure rate of PV modules under normal use conditions. Rosenthal et al. [29] found that annual failure rate was less than 0.1% for 10-year-old PV modules. In Hibberd [30], only six out of 120,000 modules up to 5-year-old PV failed, a 0.005% annual failure rate. Wohlgemuth [31] estimated that the annual failure rate of PV modules deployed from 2005 to 2008 was 0.01%. Unfortunately, to the best of the authors' knowledge, there is no data on failure rates for PV modules over 20 years old. A PV module manufacture suggested that units over 20 years-old fail at a rate of 0.5% annually [32]. It can be seen that, depending on the age of the unit, annual failure rates can vary greatly, from 0.005% to 0.5%. In addition to uncertainty over failure rates, it remains unclear what percentage of modules fail over the course of a PV system's life cycle [33]. Further, how much output is lost when a module fails remains unclear. Accordingly, the present paper adopts the result of a vast literature review by Köntges et al. [34] for input variables in the proposed ABM. They found that PV module failures lead to an output power reduction between 0% and 20%, with a mean of 10%.

3. The proposed agent-based model

3.1. Modeling purpose and case description

The purpose of the proposed ABM is to estimate the effect of PV module failures on gross output during a PV system' life cycle (i.e., net loss in output) by comparing gross generation across different routine maintenance schedules. Causes beyond failure which reduce electricity generation (e.g., the temperature of the PV module, shading PV modules from nearby obstacles, and precipitation) are not within the scope