Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 85 (2011) 111–125

SOLAR ENERGY

www.elsevier.com/locate/solener

Increasing the solar photovoltaic energy capture on sunny and cloudy days

Nelson A. Kelly *, Thomas L. Gibson

General Motors R&D Center, 480-106-269, Chemical Sciences and Materials Systems Laboratory,
30500 Mound Road, Warren, MI 48090-9055, USA

Received 9 October 2009; received in revised form 31 August 2010; accepted 23 October 2010
Available online 18 November 2010

Communicated by: Associate Editor David Renne

Abstract

This report analyzes an extensive set of measurements of the solar irradiance made using four identical solar arrays and associated solar sensors (collectively referred to as solar collectors) with different tilt angles relative to the earth's surface, and thus the position of the sun, in order to determine an optimal tracking algorithm for capturing solar radiation. The study included a variety of ambient conditions including different seasons and both cloudy and cloud-free conditions. One set of solar collectors was always approximately pointed directly toward the sun (DTS) for a period around solar noon. These solar collectors thus captured the direct beam component of the solar radiation that predominates on sunny days. We found that on sunny days, solar collectors with a DTS configuration captured more solar energy in accordance with the well-known cosine dependence for the response of a flat-surfaced solar collector to the angle of incidence with direct beam radiation. In particular, a DTS orientation was found to capture up to twice as much solar energy as a horizontal (H) orientation in which the array is tilted toward the zenith. Another set of solar collectors always had an H orientation, and this best captured the diffuse component of the solar radiation that predominates on cloudy days. The dependence of the H/DTS ratio on the solar-collector tilt angle was in approximate agreement with the Isotropic Diffuse Model derived for heavily overcast conditions. During cloudy periods, we found that an H configuration increased the solar energy capture by nearly 40% compared to a DTS configuration during the same period, and we estimate the solar energy increase of an H configuration over a system that tracks the obscured solar disk could reach 50% over a whole heavily-overcast day. On an annual basis the increase is predicted to be much less, typically only about 1%, because the contribution of cloudy days to the total annual solar energy captured by a photovoltaic system is small. These results are consistent with the solar tracking algorithm optimized for cloudy conditions that we proposed in an earlier report and that was based on a much smaller data set. Improving the harvesting of solar energy on cloudy days deserves wider attention due to increasing efforts to utilize renewable solar energy. In particular, increasing the output of distributed solar power systems on cloudy days is important to developing solar-powered home fueling and charging systems for hydrogen-powered fuel-cell electric and battery-powered vehicles, respectively, because it reduces the system size and cost for solar power systems that are designed to have sufficient energy output on the worst (cloudy) days.

Keywords: Solar energy; Renewable energy; Photovoltaic; Solar tracking system; Beam irradiance; Diffuse irradiance

1. Introduction

1.1. Solar energy utilization and solar tracking systems

Solar energy has the potential to supply an ever increasing proportion of the world's energy supply, and is the only energy source that can supply the additional energy that the world will need over the next several decades in a manner that will protect the environment and be sustainable (Crabtree and Lewis, 2007). One way to capture solar energy is to use photovoltaic (PV) cells, modules, and arrays to convert the solar energy into electricity. The electricity can be used directly or stored using batteries, or more preferably as hydrogen, i.e., any excess electricity

---

* Corresponding author. Tel.: +1 586 986 1623; fax: +1 586 986 1910.
E-mail address: nelson.a.kelly@gm.com (N.A. Kelly).

0038-092X/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2010.10.015

Nomenclature

DTS	flat-plate solar device pointed directly toward the sun (solar disk)
L	solar array with a latitude tilt (42° tilt angle with respect to the earth's surface for our site)
L + 15	solar array with a latitude tilt plus 15° (57° tilt angle for our site)
L − 15	solar array with a latitude tilt minus 15° (27° tilt angle for our site)
H	solar array with a horizontal tilt (0°, i.e., pointed toward the zenith)
G_h	global (total) horizontal radiation, W m^{-2}
I_{bh}	beam (direct) radiation on a horizontal surface, W m^{-2}
I_{bn}	beam (direct) normal radiation on a surface pointed at the solar disk, W m^{-2}
I_{dh}	diffuse (sky) radiation on a horizontal surface, W m^{-2}
PV	photovoltaic cells or modules
STC	standard test conditions (for PV cells or modules, this is an irradiance of 1000 W m^{-2} and a temperature of 25 °C)
I_{sc}	PV short-circuit current in amperes; proportional to solar irradiance
Solar irradiance	solar power per m^2, i.e., W m^{-2}
Solar insolation	solar energy per m^2, equal to solar irradiance integrated over time, W h m^{-2}
α	solar altitude angle, measured from the earth's surface to the solar disk
β	solar azimuthal angle, north–south position of the sun, directly south = 180° ($\beta = 180°$ at solar noon)
θ	solar zenith angle; also the tilt angle of a flat-plate solar collector such that it is perpendicular to direct beam radiation (provided β is at the proper angle)

not utilized directly can be used to electrolyze water to make hydrogen (Turner, 2004; Turner et al., 2008; Baykara, 2004). Hydrogen is a preferable energy carrier as it can be utilized in fuel cells for both stationary (Ipsakis et al., 2009) and transportation applications (Burns et al., 2002) where the only byproduct at its end use is water. An exciting future possibility for utilizing solar energy in the transportation sector involves distributed solar systems where individual home owners use solar energy to make hydrogen for their fuel-cell electric vehicles, or to charge their battery electric vehicles (Kelly et al., 2010). Such a scenario would be totally renewable, pollution free (with respect to tailpipe emissions) and would not need any petroleum. One important factor in moving toward this possibility is optimizing the generation and utilization of solar energy. The rest of this paper will discuss our work toward increasing the solar output from a given solar PV system.

Solar energy can be generated in large centralized plants covering hundreds of acres, such as the 14 MW installation at Nellis Air Force Base (AFB) in Nevada, or in smaller distributed applications of several kW, such as those on individual home roofs (SunPower Corp.). In between these two extremes are PV installations on large roofs, such as those on factories and warehouses. For example, General Motors currently has several large solar roof installations on factories; two in California have approximately 1 MW of solar modules, and the one in Zaragoza, Spain has approximately 12 MW of modules (General Motors Co.). The Zaragoza installation is the largest solar roof installation in the world to date. Such large solar roofs can sustainably generate much of the electricity needed at the factories, and also reduce the emissions of pollutants associated with electricity generation. These installations on flat roofs have modules with a horizontal installation.

An example of a smaller application, approximating a one-vehicle hydrogen fueler is located in Milford, MI (Kelly et al., 2008). At that site, a small (7.6 kW) array is used to electrolyze water to produce ~0.5 kg of high-pressure hydrogen gas per day – enough hydrogen to drive a fuel-cell electric vehicle (FCEV) about 30 km per day. This experimental system is a proof of concept for a home hydrogen fueling system for future FCEV owners, as the solar module area is approximately the area of a home roof, and the electrolyzer-storage-dispensing unit (ESD) could fit into a home garage.

A major obstacle to utilizing solar energy is the initial cost of the system, especially the photovoltaic (solar) modules. There is a need to minimize the cost but to maximize the efficiency, and to minimize the space used. The energy output of a given module can be increased by ~50% over that for a system with a horizontal fixed tilt by using 2-axis solar tracking, in which the flat surface of the module is always perpendicular to rays of direct beam sunshine, i.e., the module is pointed directly towards the sun (DTS). The Nellis AFB installation, mentioned above, uses 1-axis solar tracking for the approximately 70,000 solar modules installed; 1-axis tracking gives approximately 90% as much solar energy as 2-axis tracking.

Although solar tracking maximizes the collection of direct beam solar radiation, which is by far the predominant component of the incoming global or total solar radiation, it is also important to maximize the solar energy capture on cloudy days, when almost all of the solar energy is in the form of diffuse solar radiation, i.e., there is almost