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Improved photovoltaic energy output for cloudy conditions with a solar tracking system

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Abstract

This work describes measurements of the solar irradiance made during cloudy periods in order to improve the amount of solar energy captured during such periods. It is well-known that 2-axis tracking, in which solar modules are pointed at the sun, improves the overall capture of solar energy by a given area of modules by 30–50% versus modules with a fixed tilt. On sunny days the direct sunshine accounts for up to 90% of the total solar energy, with the other 10% from diffuse (scattered) solar energy. However, during overcast conditions nearly all of the solar irradiance is diffuse radiation that is isotropically-distributed over the whole sky. An analysis of our data shows that during overcast conditions, tilting a solar module or sensor away from the zenith reduces the irradiance relative to a horizontal configuration, in which the sensor or module is pointed toward the zenith (horizontal module tilt), and thus receives the highest amount of this isotropically-distributed sky radiation. This observation led to an improved tracking algorithm in which a solar array would track the sun during cloud-free periods using 2-axis tracking, when the solar disk is visible, but go to a horizontal configuration when the sky becomes overcast. During cloudy periods we show that a horizontal module orientation increases the solar energy capture by nearly 50% compared to 2-axis solar tracking during the same period. Improving the harvesting of solar energy on cloudy days is important to using solar energy on a daily basis for fueling fuel-cell electric vehicles or charging extended-range electric vehicles because it improves the energy capture on the days with the lowest hydrogen generation, which in turn reduces the system size and cost.
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1. Introduction

Solar energy is a clean, renewable way to provide electrical power, as well as to boost the future hydrogen economy in the long-term via the electrolysis of water. At the GM R&D Center, we have investigated ways to optimize the solar to hydrogen process by photoelectrochemical and photovoltaic-electrolyzer (PV-electrolyzer) systems (Kelly and Gibson, 2006, 2008; Gibson and Kelly, 2008; Kelly et al., 2008). By improving the efficiency of the solar-water-splitting process, we can help to bring a solar-powered hydrogen home fueler for fuel-cell electric vehicles (FCEVs) closer to reality. Using renewably-generated hydrogen to power future FCEVs can eliminate air emissions from vehicles and contribute to the diversity of the possible sources of hydrogen (Burns et al., 2002). Previous PV-electrolyzer systems have only been developed for the purposes of demonstration and proof of concept due to their high system costs, system complexity, and, in some cases, low system efficiencies for generating the high-pressure hydrogen needed for hydrogen storage. Although it is feasible to optimize the efficiency of PV-electrolyzer systems for making hydrogen, there is also a need to improve the individual solar and electrolysis systems (Mann and Ivy, 2004). In this work, we describe a method to improve the PV output on cloudy days using a solar tracking system.

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Photovoltaic modules are typically installed on structures such as homes or buildings using a fixed module orientation depending on the site characteristics and cost constraints. One orientation that is used on flat roofs is a horizontal (H) orientation in which the modules face straight up towards the zenith. Another configuration, that is the best overall fixed configuration for PV installations in North America, is one in which the modules face south and are tilted with respect to the ground at an angle equal to the site latitude (Lorenzo, 2003; Photovoltaic Systems Assistance Center, 1995); this is referred to as a latitude tilt. For example, in Detroit, with a latitude of approximately 42° north of the equator, the planar flat surface of the modules would be tilted at a 42° angle with respect to the ground. An ideal location for such a fixed system would be on a south-facing roof with a pitch approximately equal to the latitude tilt. The greatest amount of solar energy can be obtained for a given area of solar modules by using a mechanical tracking system so that the solar modules are always facing the sun (see Appendix A). This is referred to as 2-axis tracking since, as discussed next, two angles are needed to specify the location of the solar disk at any given time during the day.

1.1. Definition of solar angles to specify the position of the sun in the sky

The sun's location in the sky relative to a location on the surface of the earth can be specified by two angles (Iqbal, 1983). They are: (1) the solar altitude angle (α), and (2) the solar azimuthal angle (β). The angle α is the angle between the sun's position and the horizontal plane of the earth's surface, while the angle β specifies the angle between a vertical plane containing the solar disk and a line running due north.

The solar altitude angle (the sun's elevation with respect to the horizontal earth's surface) is the compliment of the solar zenith angle (the angle between the sun and a line perpendicular to the earth's surface). That is, $\alpha = 90°$ minus the solar zenith angle. The maximum solar altitude angle on a given day in the Northern Hemisphere occurs at solar noon, when the sun is directly south (i.e., $\beta = 180°$). On a sunny, cloud-free day, this will be the time of maximum solar irradiance (units of kW m^{-2}). For the winter solstice in Detroit (approximately December 21), the maximum altitude angle is $\alpha = 24.2°$, while for the summer solstice in Detroit (approximately June 21), the maximum solar altitude angle is $\alpha = 71.1°$ (US Naval Observatory). For Detroit at the time of the winter solstice, the sun rises at 8:00 AM at an azimuthal angle of 122° and sets at 5:00 PM with an azimuthal angle of 238°, moving over an azimuthal angle change of only 116°. At the time of the summer solstice in Detroit, the sun rises at 6:00 AM (daylight savings time) at an azimuthal angle of 57° and sets at 9:10 PM at an azimuthal angle of 303°, moving over an azimuthal angle change of 246°. A 2-axis PV tracking system orients PV modules so that they remain perpendicular to the sun's direct rays as the angles α and β change throughout the daylight period from sunrise to sunset at any given site.

1.2. The global solar irradiance and its components

The total (global) solar irradiance (kW m^{-2}) impinging on the horizontal surface of the earth is typically measured using pyranometers mounted horizontally to measure the irradiance over 2-π steradians (a hemisphere) Iqbal, 1983; Duffie and Beckman, 2006; National Solar Radiation Data Base (NSRDB); Wilcox, 2007; Stine and Geyer; Myers, 2005. This global horizontal radiation, G_h, is composed mainly of two components: They are: (1) beam (direct) horizontal radiation, I_{bh}, coming directly from the solar disk, and (2) sky (diffuse) horizontal radiation, I_{dh}, that is first scattered by molecules and particles, including clouds (Lorenzo, 2003; Iqbal, 1983; Duffie and Beckman, 2006; National Solar Radiation Data Base (NSRDB); Wilcox, 2007; Stine and Geyer; Myers, 2005). This is expressed by the equation:

$$G_h = I_{bh} + I_{dh} \tag{1}$$

There is also some radiation that is reflected from the ground; this will be more important for tilted surfaces than for horizontal ones, and for simplicity is neglected here. Using a pyrheliometer with a narrow field of view that is mounted on a tracking mechanism such that it is pointed at the solar disk, researchers measure the beam normal irradiation, I_{bn}, which comprises the nearly parallel rays from the solar disk. The relationship between I_{bh} and I_{bn} is:

$$I_{bh} = I_{bn} \times \text{cosine}\ (\Theta) \tag{2}$$

where Θ is the angle between the solar disk and the normal to a horizontal surface, i.e., Θ is the solar zenith angle. This is referred to as the cosine response of a light sensor; a perfect sensor would have this cosine response (referred to as a perfect Lambertian response) for beam incidence angles from 0° to 90°. Thus, as per Eq. (2), for a solar ray striking a surface at angle of 90°, the angle Θ between the ray and a surface normal is 0°, and all of its energy would be transferred (cosine 90° = 1), while for a ray grazing the surface, the angle Θ between the ray and a surface normal is 90° and no energy would be transferred (cosine 90° = 0). Notice that for a horizontally-oriented surface, the azimuthal angle is irrelevant to specifying the angle of incidence of a direct solar ray; for such a surface Θ is equal to the complement of the solar altitude angle (90° − α). For a horizontally-oriented solar module the response to direct sunshine would thus be equal to $I_{bn} \times$ cosine (90° − α), where α is the solar altitude.

Using the above, the global horizontal solar irradiance can be expressed using the well-known relationship:

$$G_h = I_{bn} \times \text{cosine}\ (\Theta) + I_{dh} \tag{3}$$

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