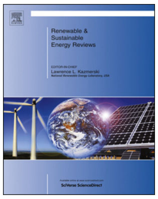
Renewable and Sustainable Energy Reviews 32 (2014) 797–809

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



# A review of icing prevention in photovoltaic devices by surface engineering

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ARTICLE INFO

*Article history:*
Received 11 August 2013
Received in revised form
20 October 2013
Accepted 4 January 2014
Available online 11 February 2014

*Keywords:*
Solar energy
Surface engineering
Icing
Hydrophobic
Self-cleaning
Transparent
Coating
Icephobic

ABSTRACT

The renewable energy sector and the solar industry, more specifically, are expected to grow in the upcoming years. However, in many colder climates worldwide, ice and snow accumulation on solar panels is prevalent and can negatively affect the efficiency or even stop the production of energy. A superhydrophobic coating has been proposed as a functional coating for use in solar cell and outdoor applications. A review of the literature has revealed that a superhydrophobic coating can be designed to display desirable characteristics that can enhance the efficiency of solar cells and prevent the degradation of efficiency over time. Five properties in relation to superhydrophobic coatings have been discussed: ice resistance, transparency, self-cleaning, antireflection, and mechanical robustness. Included in these discussions were the desired effects of the properties, and the parameters needed to optimize these properties. It was found that the water repellent properties of a superhydrophobic coating can prevent and reduce the accretion of ice, while subsequently the ice resistant properties of the composite wetting state can diminish its adhesion, making ice removal a less energy-intensive process. The good resistance to snow accumulation and the self-cleaning capabilities maintain a clean transparent substrate. Additionally, the transparency and intrinsic antireflective effects can be optimized to ensure maximum light transmission and increased efficiency. A stable and mechanically robust coating would allow for minimal maintenance, prolong the benefits of sought after properties, and increase the overall useful life of a solar panel.

## Contents

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http://dx.doi.org/10.1016/j.rser.2014.01.015

## 1. Introduction

With advances in technology and the recent shift in mindsets toward sustainability, the renewable energy industry has become a more viable source to meet the energy needs of the world and is being widely researched in all areas [1–5]. In 2010, The U.S. Energy Information Administration's International Energy Outlook reported that renewable energy will be the fastest growing world energy source over the period 2007–2035 [6]. The increase in this demand may be attributed to several factors: the decline in fossil fuels, climate change, and the abundance of renewable energy potential (Table 1). The migration away from fossil fuel usage is an appropriate response to the knowledge that fossil fuel resources are finite and cannot sustain society indefinitely [5,7]. As of 2010, oil production had been nearly static for the past 5 years and marginal productivity was showing signs of stress worldwide [7]. Renewable energy has dawned as a possible solution that may alleviate the growing concerns over greenhouse gas emissions, increasing energy prices, and the dependency on foreign energy sources, and this includes the geopolitical climate that is associated with the production of fossil fuels in some regions of the world [8]. In addition, renewable energy offers the benefits of being clean, abundant, inexhaustible, and for a variety of applications it can even be the most cost-effective source of energy, meeting between 15 and 20% of the total world energy demand as of 2007 [9].

In many places where renewable energy systems are used, climactic conditions are severe and icing is prevalent. This is a problem because the efficiency of wind turbines and solar devices is greatly reduced due to icing and snow accumulation; it may even stop the production of energy all together [1,11–13]. Due to the crippling effect ice accretion has on the ability of solar devices to produce electricity, many researchers have been turning their attention to designing systems of ice removal. The removal of ice can be classified into two categories: active solutions and passive solutions. Active solutions are methods of removing ice after it has been deposited; these include mechanical scraping, thermal treatments, and the use of de-icing fluids. Passive solutions would include treatments that can be applied to a surface prior to its use that would prevent the ice from adhering or cause it to delaminate under its own weight. Active methods are currently widely used, but passive methods have found few industrial uses despite being environmentally friendly, compared to de-icing fluids. Passive methods also represent a cheaper option than active methods which are energy hungry and can be expensive to produce and operate [14]. One such possible passive solution may lie in hydrophobic coatings. Currently, there is no known material that can completely prevent ice or snow from accumulating on its surface; however, some coatings are believed to provide reduced adhesion [15] and for smooth surfaces, there is a clear trend that the ice adhesion strength decreases as the surface becomes more hydrophobic [16].

## 2. Hydrophobic surfaces

Hydrophilicity refers to the physical property of a material that can transiently bond with water through hydrogen bonding. A water droplet will spread itself on a hydrophilic surface; it may also enter the pores of the material and completely saturate it. Most natural materials are hydrophilic. A water droplet on a hydrophilic surface will occupy as large a surface as possible, thus making the water contact angle significantly low. Hydrophobicity refers to the physical property of a material that repels a mass of water. A water droplet being repelled by the material will not touch a large area of the surface and will take a spherical shape, thus making the water contact angle very large. The evaluation of hydrophilicity and hydrophobicity are made through measuring the angle at which water contacts a surface.

A surface with a water contact angle greater than 90° is usually referred to as hydrophobic, and one with a water contact angle higher than 140° is qualified as ultra-hydrophobic. The surfaces with very high water contact angles, particularly greater than 150°, are usually called superhydrophobic surfaces. The contact angle of water has been commonly used as a criterion to evaluate the static hydrophobicity of a surface, as depicted in Fig. 1. Alone, however, that factor is not adequate for the evaluation of dynamic hydrophobicity, which is the sliding of water droplets. Dynamic hydrophobicity is describing a surface's ability to shed water. Furthermore, to completely describe a superhydrophobic state, the contact angle hysteresis should also be measured. For an optimal superhydrophobic state, the static contact angle should be maximized, and the contact angle hysteresis minimized [17].

### 2.1. Contact angle hysteresis

The contact angle hysteresis is the difference between the advancing and receding contact angles. The sliding angle and/or the contact angle hysteresis are commonly utilized as criteria for dynamic hydrophobicity on a solid hydrophobic surface [17]. Hysteresis is a phenomenon that can arise from the molecular interactions between the solid and liquid or from irregularities in the surface, such as roughness or heterogeneities. In the case of a sessile drop: when further liquid is added, the contact line advances forward. When the motion of the drop stops it exhibits an advancing contact angle, $\theta_A$. However, if liquid is removed from the sessile drop, the contact angle decreases before the contact line retreats back to a receding value, $\theta_R$. The contact angle hysteresis is referred to as the difference between $\theta_A$ and $\theta_R$. Furthermore, in the case of a droplet moving along the solid surface, the contact angle that appears at the front of the droplet, $\theta_A$, will be greater than that at the back of the droplet, $\theta_R$. This is due to roughness and surface heterogeneity, resulting in the contact angle hysteresis [18,19].

### 2.2. Origin of hydrophobic surfaces

The phenomenon of hydrophobicity and self-cleaning surfaces was observed for the first time in nature. The term “Lotus effect” is accredited to the botanist Wilhelm Barthlott [20,21] and refers to a special ability of the Lotus. The Lotus flower can stay clean and unaffected by dirt and pollution, even when growing in muddy waters. The Lotus leaf's “self-cleaning” surface, which reaches water contact angle values greater than 150°, is hydrophobic and rough. Its surface is composed of two layers, a lower layer of micro-sized roughness covered by a second waxy layer of hydrophobic crystalloids of nano-sized roughness. The self-cleaning mechanism is characterized by three properties: superhydrophobicity, low sliding angle, and removal of dirt particles by the sliding droplet [22]. The amazing functions and capabilities of the Lotus, like other biological species, have developed over millions of years through evolution (Fig. 2). The ambition to recreate biological systems found in nature has sparked interest in a wide range of research and has led to the