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Avoiding Snow and Ice Formation on Exterior Solar Cell Surfaces - A Review of Research Pathways and Opportunities

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Abstract

Today energy-efficient and energy-harvesting buildings experience an ever-increasing interest and demand. Building integrated photovoltaics (BIPV) may in this respect represent a powerful and versatile tool for reaching the goal of zero energy and zero emission buildings. The BIPV systems replace the outer building envelope skin, thus serving simultanously as both a climate screen and a power source generating electricity. However, snow and ice formation on the exterior solar cell surfaces reduce their performance and may also lead to faster deterioration. Hence, if one could find a way to develop solar cells which were able to avoid snow and ice formation on their surfaces, one would have moved a large step ahead. This work presents a review exploring miscellaneous pathways for avoiding snow and ice formation on solar cell surfaces including superhydrophobic and icephobic surfaces.

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Keywords: Snow; Ice; Solar cell; Building integrated photovoltaics; BIPV; Surface; Review; Research pathway; Superhydrophobic; Icephobic.

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1. Introduction

Energy and environmental aspects are pushing the development of energy-efficient and energy-harvesting buildings including zero energy and zero emission buildings for a sustainable built environment. In this respect there is an increasing interest to make use of building integrated photovoltaics (BIPV) [1-8]. A BIPV system replaces the outer building envelope skin, thus serving simultanously as both a climate screen protecting towards outdoor weather conditions and as a power source generating electricity from the incident solar radiation. Two examples of BIPV integrated seamlessly in the building roofs are shown in Fig.1 [9,10]. BIPV systems with their specific properties need to fulfil the requirements of both the building envelope skin, e.g. weather protection versus e.g. rain and wind [11-12], and the solar cells, e.g. solar cell efficiency and maximum power output [5,8].

Fig.1. BIPV examples on building roofs (left [9] and right [10]).

It is important that the solar cells can utilize as much as possible of the available solar radiation throughout the day and the year. Snow and ice formation on the exterior solar cell surfaces reduce their performance and may also lead to faster deterioration. Thus, research should be conducted to develop solar cells being able to avoid snow and ice formation on their surfaces. This challenge may be attempted solved through different pathways [13]. Several of these pathways involve the development of specific and tailor-made surfaces, often by micro- and nanostructuring of the surfaces. These material technologies include among others the development of hydrophilic, superhydrophobic and icephobic surfaces.

Hence, the objective of this study is to present a review exploring miscellaneous research pathways and opportunities for avoiding snow and ice formation on exterior solar cell surfaces including superhydrophobic and icephobic surfaces.

2. Snow and ice formation on solar cell surfaces

The interaction between snow, ice and the substrate material, e.g. the exterior solar cell surface, is a complex matter to study. Snow and ice exist in countless variations. For example, Magono and Lee (Gray and Male [14]) have classified 80 different natural snow crystals, where particles such as ice pellets and hail are not included. Moreover, snow and ice interactions with various substrates and climate conditions in general create yet another set of numerous snow and ice types. The different variations depend on a vast number of factors like e.g. atmospheric conditions, climate conditions, weather exposure, temperature, pressure, changes during time (e.g. snow ageing), incident solar radiation and various pollutions among others. It should also be noted that snow may be considered as a very hot material as relatively large and fast material changes occur around the melting point at 0°C (e.g. numerous snow/ice/water variations), i.e. compared with many other solid state materials with much higher melting points (e.g. iron at 1538°C), hence complicating the matter at hand even further.

The active solar cell layer is normally covered by a glass material, often with an exterior smooth surface. Nevertheless, snow and ice will often stick to the solar cell surfaces for shorter or longer periods. Thus, manual and mechanical methods may be employed to remove the snow attached to the solar cell surfaces (Fig.2 [15,16]), which also introduce a risk to damage the solar cells.

Depending on the climate conditions snow and ice may strongly adhere to the exterior glass surface on the solar cells even at large inclination angles. In Fig.3 there is shown a stand-alone solar cell panel covered by snow at an inclination angle of 70° and a snow/ice slab strongly adhering to the glass surface of an insulated window pane even at an inclination angle of 90° during a laboratory experiment [13].

Fig.2. Manual and mechanical methods for removing snow from solar cell roofs (left [15] and right [16]).

Fig.3. Snow covering a solar cell panel at an inclination angle of 70° (left) and a snow/ice slab strongly adhering to the glass surface of an insulated window pane even at an inclination angle of 90° during a laboratory experiment (right) [13].

In addition to photovoltaic solar cells, development of materials able to avoid snow and ice formation on their surfaces, will be important for many other application fields, e.g. solar thermal panels, roof windows, electrical power transmission lines, wind turbine blades, car and pedestrian roads, traffic and other information signs, and surfaces of cars, trains, ships and airplanes. That is, the development of snow and ice avoiding materials has a very large potential in several areas.

3. Self-cleaning surfaces

Self-cleaning window glass panes already exist commercially, which are supposed to decrease the need for manual cleaning substantially. Most of these glass panes function by applying a photocatalytic coating like e.g. titanium dioxide (TiO_2) on the outer glass surface, where the incident ultraviolet (UV) solar radiation reacts with this coating to break down organic dirt. Thereafter, rain water spreads evenly over the hydrophilic surface and runs off in a ”sheet” taking loosened dirt with it, hence drying quickly without leaving stains or streaks. Note the study by Midtdal and Jelle [17] presenting a state-of-the-art review on commercially available self-cleaning glazing products along with future research pathways.

The commercial self-cleaning products may according to their operational state when purchased be divided into factory- and user-finished products [17]. Factory-finished products cover all factory produced glazing products (e.g. windows) where a self-cleaning surface is already operational when purchased. User-finished (user-do-it-yourself) products involve liquid products, either in form of a spray or a roll-on applicator, which can be applied by the user to existing glass surfaces to obtain a self-cleaning coating or film on top of the regular glass pane or any other material.

Different strategies are applied and pursued for achieving a self-cleaning effect, where these may be categorized into the following surface characteristics:

- Photocatalytic hydrophilic surface.
- Superhydrophobic or ultrahydrophobic surface.
- Microstructured or nanostructured surface.

Commercial factory-finished self-cleaning products are most often based on photocatalytic hydrophilic coatings or surfaces, whereas user-finished self-cleaning products are normally based on the creation of hydrophobic coatings on the desired surfaces. In the following we will see that there exists an important correlation between superhydrophobicity and a structured coarseness of a surface, whereupon the term icephobicity will also be discussed. As a general rule of thumb, the coarseness dimensions of the structured self-cleaning surface should be smaller than the dirt particles to be removed by the self-cleaning effect.

4. Surfaces attempting to avoid snow and ice formation

4.1. General

This review will focus on material surface technologies created for making exterior solar cell surfaces able to avoid snow and ice formation, and in this respect a special emphasis will be given on superhydrophobic and icephobic surfaces. Other possible pathways do also exist, e.g. various architectural solutions or the possibility of making a low friction non-sticky surface [13]. With snow and ice formation it is meant any natural outdoor process which may lead to snow and ice covering the solar cell panels. Examples may be regular snow downfall, rain which later undergoes a freezing process, and condensation and freezing processes from moisture in the ambient air.

Any surface modifications, e.g. nanostructuring, on the exterior solar cell surfaces should not decrease the amount of solar radiation absorption in the wavelength range useful for generating electricity. Hence, for cases where the surface modifications are not made directly in the active solar cell material itself, these modifications have to be made in a material as transparent as possible for solar radiation, e.g. in the exterior glass material or anti-reflection coating. Thus, opaque coatings or materials lowering or blocking the solar radiation transmission to the active solar cell material can not be used.

It should be noted that we are searching solutions which do not consume additional energy or use energy which otherwise could have been utilized as an energy gain in the actual building. That is, e.g. applying electrical heating cables, utilizing a heat loss from the building (any heat loss should be minimized) and using solar energy in a wavelength range which otherwise could have been utilized to produce electricity, are not considered as viable solutions in this context.

4.2. Repellent surfaces

In general, ideally a solar cell surface should repel all there is except the useful part of the solar radiation utilized for electricity generation. Thus, various kinds of dirt should also be repelled from a solar cell surface, i.e. self-cleaning surface technologies may be used for this purpose. Furthermore, the self-cleaning surface, e.g. a coating, should not decrease the absorption of solar radiation by the solar cell active material. Another issue worth mentioning in this respect is that a solar cell should absorb as much as possible of the solar radiation as long as the radiation is being converted to electricity in order to achieve as high solar cell efficiency and electrical power output as possible, whereas the amount of solar radiation not utilized for electricity production should ideally not be absorbed as heat as a higher temperature on silicon-based solar cells will reduce their solar cell efficiency. However, if the non-utilized (for electricity generation) part of the solar spectrum could be used for avoiding or removing snow and ice, that is another matter.

Hydrophobicity is an often used measure of the repellent nature of a surface, and then especially to repel water. A completely hydrophobic surface has a water contact angle of 180°, whereas a completely hydrophilic surface has a water contact angle of 0°. A surface is considered as hydrophilic for water contact angles below 90°, hydrophobic above 90°, superhydrophilic below 5° (within 0.5 s or less) and superhydrophobic above 150° [18-21].

The hydrophobicity of a surface will be dependent upon (a) the micro- and nanoscale coarseness of the surface, and (b) the surface energy of the surface, where the former one may be considered as a mechanical property and the latter one as a chemical property, respectively. Generally, a micro- or nanoscale coarse surface and a low surface energy will give a hydrophobic surface. A low surface energy can be achieved by use of reactive molecules mainly classified into four categories, i.e. fluorinated molecules, alkyl molecules, non-fluorinated polymers and silicon/silane compounds [20,22].

4.3. Micro- and nanostructured surfaces

The coarseness of a surface on a micro- and nanoscale has a direct influence on its repellent and hydrophobic properties. The wetting states of a liquid drop placed on a surface are illustrated in Fig.4 depicting a smooth surface (where contact angle measure is shown), the Wenzel state, the Cassie-Baxter state and a combined state [23], where the Cassie-Baxter state represents the superhydrophobic state where liquid drops are repelled as spheres from the surface (large contact angle). In the Wenzel state the liquid (water) drops are impaled by the nanorods (or similar structure) on the surface, while in the Cassie-Baxter state the liquid drops are resting on top of the nanorods with trapped air pockets beneath between the nanorods.

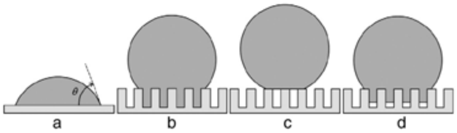
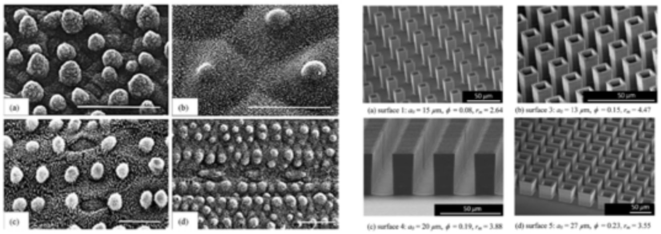


Fig.4. Wetting states of a liquid drop to a surface: (a) drop on a smooth surface (contact angle measure is illustrated), (b) Wenzel state, (c) Cassie-Baxter state, and (d) combined state [23].

4.4. Superhydrophobic surfaces

Superhydrophobic self-cleaning surfaces are aiming at repelling the water from their surfaces. As an example, Fürstner et al. [24] investigated the superhydrophobic properties of an artificial lotus leaf (Nelumbo nucifera), which was found to have excellent self-cleaning abilities, with a contact angle of about 158°. The study also tested artificial metal surfaces with superhydrophobic abilities with a contact angle of almost 165°, which was found to remove over 98 % of the contaminants on its surface after it was subjected to artificial contamination and rinsing. Moreover, some other metal specimens removed close to 100 % of the contaminants. Thus, these results indicate that with the technology today it could be possible to tailor-make self-cleaning superhydrophobic products, although there also exist studies which show less self-cleaning effects with hydrophobic surfaces. Examples of natural water-repellent leaf surfaces and artificially fabricated superhydrophobic surfaces are shown in Fig.5 [25,26].



(a) surface 1: $a_0 = 15\ \mu m$, $\phi = 0.08$, $r_w = 2.64$
(b) surface 3: $a_0 = 13\ \mu m$, $\phi = 0.15$, $r_w = 4.47$
(c) surface 4: $a_0 = 20\ \mu m$, $\phi = 0.19$, $r_w = 3.88$
(d) surface 5: $a_0 = 27\ \mu m$, $\phi = 0.23$, $r_w = 3.55$

Fig.5. Micromorphologies for water-repellent leaf surfaces of (a) Nelumbo nucifera and (b) Lupinuspolyphyllos (scale bars = 50 µm); and (c) Gladioluswatsonioides and (d) Sinarundinaria nitida (scale bars = 20 µm) (left four photos) [25]. Images of four artificially fabricated hollow hybrid superhydrophobic surfaces (scale bars = 50 µm) (right four photos) [26].

The task of preventing snow and ice formation involves other crucial aspects than merely removal of dirt from these surfaces. Freezing of water below 0°C represents a huge obstacle or challenge in this respect, which in some cases is further complicated by in general possible moisture condensation from surrounding air and subsequent freezing on the surfaces, and as a specific example by possible ice or frost formation on the surfaces at air temperatures above 0°C due to thermal infrared radiation loss to a cold sky and thus possible lowering the actual surface temperatures below 0°C.

4.5. Icephobic surfaces

Several of the same principles may be applied for anti-icing investigations as for self-cleaning aspects, in particular superhydrophobicity and structured surface coarseness effects, and thereby the term icephobicity has been introduced and is now in common usage.

Anti-icing coating design cases with various roughness scales, including microscale roughness, nanoscale roughness and hierarchical roughness (combination of both micro- and nanoscale) are illustrated in Fig.6 [27].

Micrographs of various surface structures for icephobicity are shown in Fig.7, depicting nanocones, nanopits, micropillars and micropillars with embedded nanotextures [28]. Furthermore, Fig.7 also shows the effects of a nano-fluorocarbon coating on icing processes, where the water droplets on the coated surface have a much smaller contact area to the superhydrophobic surface, i.e. water spheres due to the large contact angle caused by the superhydrophobicity, resulting in a much longer starting time for icing and also a much longer total time needed to complete the whole icing process for the superhydrophobic surface than for the non-coated plain surface [29].

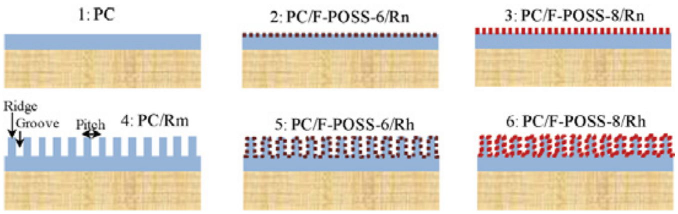


Fig.6. Anti-icing coating design cases where Rn denotes nanoscale roughness, Rm microscale roughness, and Rh hierarchical roughness [27].

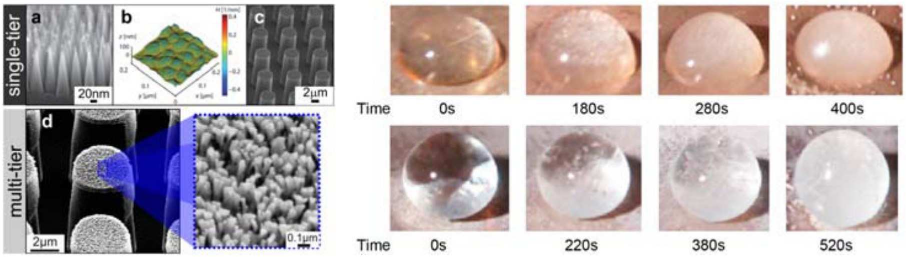


Fig.7. (left) Micrographs showing relevant length scales and structures utilized in single-tier and multi-tier structures for icephobicity: (a) etched Si nanocones, (b) etched SiO_2 nanopits, (c) etched SiO_2 micropillars, and (d) etched Si micropillars/nanotextures with the nanotexture depicted in the inset image [28]. (right) Icing process of a water droplet on a plain copper surface (top) and a nano-fluorocarbon coated surface (bottom) [29].

Icephobicity and anti-icing aspects are being investigated through several studies in the literature (e.g. [19,27-33]), where most of these focus on superhydrophobic surfaces by nanostructuring. However, although many promising results have been achieved, e.g. for prolonged freezing delays on superhydrophobic surfaces, there is still much research to be carried out before practical and efficient snow and ice avoiding/repelling surfaces for a full range of outdoor weather exposure have been accomplished.

4.6. Further research perspectives

Naturally, the research on superhydrophobic and icephobic surfaces will continue, which may ultimately find their way to practical applications for avoiding snow and ice formation on the exterior surfaces of solar cells. However, other solutions might be possible and may yet be waiting to be discovered.

An interesting research pathway may be to investigate if it is possible to make some sort of force field solution. That is, to envision a force field which could repel all snow crystals already before they are impacting onto the solar cell surfaces, in addition to prevent any ice formation on the exterior surfaces (e.g. rain which freezes, and condensation and freezing processes from moisture in the ambient air). Hence, one has to ask what kind of force field this could be, which in addition is (ideally) not using extra energy. An electric or magnetic force field, or a combination of these, either static or dynamic, may be investigated. Or could something entirely different be envisioned? In order to be able to repel the snow crystals one may explore if the dipolarity in water molecules may be taken advantage of and utilized, even in solid state as snow and ice and not as liquid water, or the various transition states (gas, liquid and solid state) at the solar cell surfaces.

One may also attempt to develop a self-heating material solution, where the material or solution technology may utilize free radiation to remove (e.g. melt) the snow and ice covering or starting to cover the solar cell surfaces [13]. With free radiation it is meant radiation which can not or will not be utilized as part of the energy harvest of the building, i.e. radiation energy which otherwise may not have been utilized in solar cell panels (or e.g. solar thermal panels). The free radiation may then comprise the part of the solar radiation spectrum which can not be utilized by the actual solar cells (e.g. part of the near infrared radiation) and ambient infrared thermal (heat) radiation. Snow downfall is normally occurring when there is no direct solar radiation, which needs to be accounted for when attempting to utilize parts of the solar spectrum for snow and ice. It should also be noted that the above considerations may be possible for photovoltaic solar cell panels, but not so obviously feasible for solar thermal panels, as the thermal panels may in principle utilize all the solar and infrared radiation.

The durability and robustness of the developed materials and surfaces have to be investigated. For example, nanostructured and superhydrophobic surfaces have to withstand the different climate exposures for a satisfactory long time period, including various mechanical wear and tear and freezing/thawing cycles. Naturally, one may not cover these surfaces with just any protective coatings as these would then block the properties of the tailor-made nanostructured surfaces beneath. If any protective coating will be necessary such a coating or rather the resulting new surface would need to exhibit the same snow and ice avoiding properties as the original surface beneath, e.g. a very thin layer following and maintaining the nanostructered surface and e.g. also chemically upholding any superhydrophobic properties. In general, to study the durability of building materials and components, also newly developed ones, e.g. by carrying out accelerated climate ageing in the laboratory, is of major importance [34]. Hence, performing a robustness assessment of these materials and components may also be found to be beneficial [35]. Various durability aspects for self-cleaning and superhydrophobic surfaces are given in the literature [36-38].

Finally, note that natural superhydrophobic surfaces like e.g. plant leaves and insect wings when damaged may regenerate their surfaces by biological growth processes and thus are able to maintain their superhydrophobicity over their whole lifetime. Hence, one may ask if it could be possible to make artificial superhydrophobic surfaces which would continuously regenerate their surface patterns and thereby retain their superhydrophobic properties, i.e. self-healing, self-repairing or self-regenerating superhydrophobic surfaces, see e.g. Men et al. [39] and Verho et al. [40].

5. Conclusions

Snow and ice formation on exterior solar cell surfaces decrease their performance. Energy-efficient and energy-harvesting buildings applying building integrated photovoltaics (BIPV) should be able to avoid any formation of snow and ice on their solar cell surfaces in order to utilize as much as possible of the incoming solar radiation. This study reviews various research pathways and opportunities for avoiding snow and ice formation on solar cell surfaces with a special emphasis on the development of materials with superhydrophobic and icephobic surfaces.

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