A Review of Possible Pathways for Avoiding Snow and Ice Formation on Building Integrated Photovoltaics

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Abstract

As building integrated photovoltaics (BIPV) are becoming more widespread, the demand to utilize the technology in the best way with respect to several aspects, e.g. durability, efficiency, power output and aesthetical considerations, will be increasing. Thus, there will also be a growing focus on how to avoid snow and ice formation on the exterior surfaces of BIPV, especially in colder regions.

During the winter period there is much less incoming solar radiation, however, this is also the period when the solar radiation is most needed, both for heating and daylight purposes. In addition, snow and ice covering the solar cell surfaces may also lead to a more rapid degradation. The task to avoid snow and ice formation is rather challenging, due to the fact that snow, ice and ambient weather conditions come in countless variations and processes. Snowfall, freezing of rain water and condensation of air moisture and subsequent freezing, are examples of aspects that have to be taken care of in a satisfactory way.

The review study presented herein discusses the various possible research pathways for surfaces designed to avoid or reduce the accumulation of snow and ice, and looks especially at the properties, requirements and opportunities for BIPV applications. A special emphasis is given on materials science research aspects like e.g. self-cleaning, micro- and nanostructured, superhydrophobic and icephobic surfaces.

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1. Introduction

With the ever increasing number of installed photovoltaic (PV) systems, the need for efficiency and aesthetics have risen as well. To this end, building integrated photovoltaic (BIPV) installations have been developed and begun to be in demand. With this growing market comes the demands that installations should produce electricity steadily over time, be reliable and yield a good return-of-investment.

In cold and polar regions (Peel et al., 2007), one obstacle to be overcome in order to achieve this, is the removal of snow and ice from the panel surfaces. Snow and ice accretion reduces energy production to near zero very quickly and must therefore be removed. This can, however, present some risks and disadvantages. Methods may vary, but common factors include risk of personal injury (e.g. from falling from a slippery roof) and risk of damaging the panel surfaces with various tools (Jelle et al., 2016).

Another challenge is the need for low cost solutions. As power production is lower in winter time due to the low incident angle of light, the potential gain of removing the snow must outweigh the added cost of the chosen solution.

A proposed strategy that has been investigated the last few years is to make the surface passively repel all snow and ice formation in a similar manner to superhydrophobic surfaces that repel water. Some disbelief in the applicability of the concept exist as a truly icephobic surface with consistent robust results has yet to be presented (Parent and Ilinca, 2011).

The term icephobic is commonly used but is somewhat poorly defined. Some refer to low adhesion strength between ice and a solid surface (Kulinich and Farzaneh, 2009; Menini and Farzaneh, 2011), others refer to the prolonging of freezing time of sessile or falling water droplets (Guo et al., 2012; Jung et al., 2012, 2011). Hejazi et al. (2013) have summarized these definitions with three conditions of icephobicity; (i) preventing the freezing of water condensing on the surface (frost), (ii) preventing the freezing of incoming water, and (iii) if ice is formed, it should have a low adhesion strength (Hejazi et al., 2013). Regardless of the exact definition, icephobic implies that the surface should passively repel all snow and ice for as long as possible, and optimally retain this characteristic over time.

There are several alternative strategies to tackle the problem of ice and snow. Active solutions like heating cables used in car windows or the use of water to melt the ice, run into the problem of energy consumption. As PVs in cold climate regions produce a reduced amount of energy, it must be utilized as effectively as possible and the melting of ice require a tremendous amount of energy (Jelle, 2013). Chemical de-icing strategies contribute to the environmental degradation and should thus be avoided. It is currently used in aeronautics as no viable alternatives exist (Parent and Ilinca, 2011).

An icephobic surface is arguably the best option for BIPVs. In attempting to obtain such a surface, several strategies have been explored (He et al., 2011; Irajizad et al., 2016; Kako et al., 2004; Rykaczewski et al., 2013). In this study, these strategies will be described and evaluated with respect to their strengths, weaknesses and potential for further development and future research in section 3.

2. Challenges of nature

Integration of PVs in buildings imply that they replace part of a building's traditional envelope and act as both PV panels and as building envelopes. This places special requirements on BIPVs to, not only to produce electricity steadily and efficiently, but also to be mechanically strong enough to withstand the rigors of weather and wind in a potentially harsh climate.

In some parts of the world, like the arctic regions, icing and snow coverage is a real problem as snow coverage can remain during a significant part of the year (Peel et al., 2007), (Dietz et al., 2012), reducing the productive period significantly in a region that has a lower incident light intensity (Duffie and Beckman, 2006). In addition, ice and snow comes in many different forms (Gray and Male, 1981; Magono and Chung, 1966), and while a strategy might work adequately for the repelling of ice formed by supercooled rain falling on a surface, it might not be as effective in handling other forms of ice, e.g. frost (Rykaczewski et al., 2013; Varanasi et al., 2010).

A successful design of an icephobic surface must thus resist a broad range of weather conditions and do so consistently over a long period of time to ensure consistent energy production over the entire life span of the BIPV product. These weather conditions will be briefly described below, along with eroding and ageing factors such as hail, wind and UV radiation.

2.1. Frost

Frost is a term that contains a multitude of different forms of ice crystal formations. In this study, the term "frost" will be used as a general term.

Frost is generally formed in two ways; Desublimation of water vapour from cold air onto a substrate, or freezing of water droplets formed by condensation (Na and Webb, 2003). Condensation occurs when the temperature of humid air reaches below the dew point by encountering a cold surface. If the substrate temperature is below the freezing point of the water droplets, frost will form on the surface (He et al., 2011). The droplets will stay in the liquid state until ice nucleation and growth occurs and the droplets freeze. The time required is theoretically dependent on the size and shape of the droplet (melting point suppression by size effects), the temperature of the water, the substrate and the atmosphere as well as the heat exchange rate with the surface and the atmosphere (He et al., 2011).

Desublimation is a process that occurs when the water vapour pressure is high but will always be a secondary process to freezing of condensation that requires lesser vapour pressure to form (Na and Webb, 2003). One might imagine a situation of rapid atmospheric cooling where the desublimation process becomes favourable, such as extra-terrestrial applications, but for the application of BIPVs, the condensation process is the common and thus more interesting aspect.

2.2. Fog and mist

Fog forming under cool conditions may result in rime. This is a variation of frost that occurs as a result of airborne condensed water droplets adsorbing on a cold substrate, where they subsequently freezes, resulting in needle-like structures stretching in the direction of the prevailing wind (Sojoudi et al., 2016).

2.3. Supercooled rain and drizzle

Supercooled rain and drizzle occur when the water droplets falling are at a temperature lower than the equilibrium freezing temperature, sustained by the droplet curvatures effect on thermodynamic equilibrium (Schutzius et al., 2014). These droplets then hit a surface, conform to the host surface changing the liquid-gas interface curvature, and thus ice nucleation can occur. This kind of precipitation can result in glazing of surfaces like PV modules and roads, break-down of power lines, and stalling aerofoil aircraft (Cao et al., 2009).

2.4. Snow

In the tentative definitions in normal use for icephobicity, there is rarely an inclusion of the repellence of snow. This is possibly due to the difference in behaviour and characteristics of snow. Therefore, the term snowphobic will hence be used to describe this.

Snow is generally separated in two main categories depending on the liquid water content; wet and dry snow. Wet snow is associated with temperatures close to the freezing temperature, whereas dry snow is associated with lower temperatures. Sojoudi et al. (2016) suggest an approximate temperature limit of -1 or -2°C, below which the snow can be considered dry, and above which it can be considered wet.

Wet snow has a tendency to accumulate on almost any surface and is a well-known problem area for power lines and rooftops. The added weight can collapse power lines and cave in roofs, leading to a necessary over-dimensioning with respect to loadbearing capacity. In this respect, a snowphobic surface has the potential to reduce construction costs.

The adhesion of dry and wet snow to a surface can differ somewhat, as well as between wet snow with different water contents. It also differs between types of surfaces. Kako et al. (2004) showed that a superhydrophobic surface has low adhesion to snow compared to other kinds of surfaces, owing to the resistance to the water layer, but requires a larger weight of wet snow for sliding off the surface. Dry snow, however, was seen to be shed preferentially by the superhydrophobic surface (Kako et al., 2004).

2.5. Hail

Hail is a type of precipitation that can have a significant impact on a sensitive surface like a structured superhydrophobic surface, where the structural integrity of the surface might be compromised by the bombardment of ice pellets at high velocities.

Created in the atmosphere at high altitudes, the impact velocity of hail can be quite high and thus the potential damage significant. The size of hail pellets can vary greatly, from a few millimetres to several centimetres in extreme cases. It is thus highly relevant to design surfaces that can withstand regular incidents of hail in the most common size ranges, be it by mechanical strength by use of some self-healing strategy.

2.6. Wind and UV radiation

Wind is a factor of nature that can be unpredictable. Bringing with it leaves, sand, insects and other contaminants, strong winds can have an effect of mechanical wear on a sensitive surface.

UV radiation can also have a deleterious effect on a sensitive surface. Especially on a polymer surface or polymer based coating that might suffer from UV decomposition. It is thus an important factor to bear in mind when designing surfaces in general and especially otherwise sensitive surfaces.

2.7. Dirt and dust

Winds and precipitation can carry with it a lot of debris, e.g. dirt and dust during dry summer days. The accumulation of debris along with wind and water, can lead to significant wear on an icephobic surface. For a structured superhydrophobic surface the structure may be ruined and the icephobicity lost. It is therefore beneficial if the surface is both self-cleaning and self-repairing in addition to icephobic.

3. Icephobicity strategies

Most strategies for attaining icephobicity start with hydrophobicity (Antonini et al., 2011; Schutzius et al., 2014). This is a natural place to start as a large part of precipitation that contributes to ice accretion, is in the form of liquid water. This does not, however, imply that hydrophobicity equals icephobicity, as pointed out by Hejazi et al. (2013) among others (Hejazi et al., 2013; Nosonovsky and Hejazi, 2012).

Superhydrophobic surfaces have also been shown to be useful with regards to other aspects like self-cleaning behaviour (Midtdal and Jelle, 2013).

Another aspect to consider is durability. In this respect, many superhydrophobic surfaces are not so well suited. To overcome this, some propose using more durable materials or materials with intrinsic hydrophobic behaviour, like polydimethylsiloxane (PDMS). Several attempts have also been made to imbue superhydrophobic surfaces with self-healing abilities (Ionov and Synytska, 2012; Li et al., 2010; Wang et al., 2011), but results have shown limited practical applicability (Ionov and Synytska, 2012).

Combining the hydrophobicity with the ability to prevent frost, shed snow and ice, while preventing or delaying supercooled rain from nucleating on the surface is thus the primary goal of this icephobicity strategy.

Other strategies attack the problem from unexpected directions, like using water to repel ice and snow. Relying on a superhydrophilic surface and the near-perfect wetting of such a surface, Kako et al. (2004) presented such a method for the shedding of snow.

Different strategies are reviewed below and evaluated with respect to strengths and weaknesses by examples of their reported results.

3.1. Structured surfaces

One of the most widely used strategies for attaining superhydrophobicity is by use of a textured surface and several variations of these exist. Each level of structuring is reviewed below and related to each other with respect to experimental results.

3.1.1. Microstructured surfaces

Microstructured surfaces have proven to be an effective means of attaining superhydrophobicity and have therefore been evaluated with respect to a possible implementation as icephobic surfaces.

Varanasi et al. (2010) investigated the effects of frost formation on superhydrophobicity as applied on a microstructured superhydrophobic silicon surface. They show that whenever frost can form on the surface of a structure the result is a loss of superhydrophobicity of the surface as a whole. This was done by investigating frost accretion on an ordered rod-type microstructured surface where frost was seen to form as a porous layer on the rods (*see Figure 1*). This is consistent with work carried out by Rykaczewski et al. (2013). They also found frost to deplete oil from their SLIPS type microstructured surface. This is discussed further in the "Liquid infused surfaces" -section below.

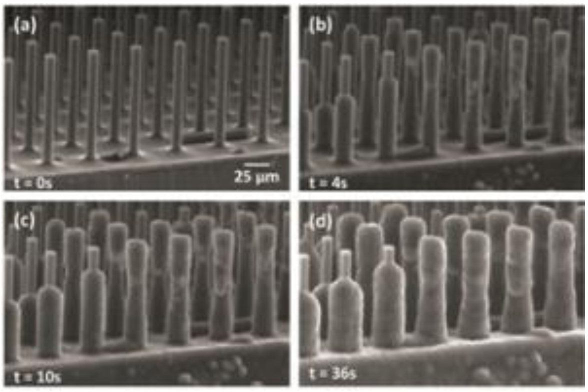

Figure 1: Image produced by Veranasi et al. showing frost accretion on a microstructure (Varanasi et al., 2010).

One of the more studied aspects of icephobicity, is the freezing delay of sessile or impacting droplets. Dash et al. (2012) investigated the superhydrophobic behaviour of a robust microstructure geometry with respect to impacting droplets in order to determine the governing aspects of droplets being pinned in the Wenzel state as opposed to being repelled and to the Cassie-Baxter state.

They identify a critical velocity, dependent on surface morphology and thus capillary pressure, above which pinning in the Wenzel state occurs (*see Figure 2*). This is explained as a result of water extending down into the microstructure when the hammer pressure overcomes the capillary pressure (Dash et al., 2012).

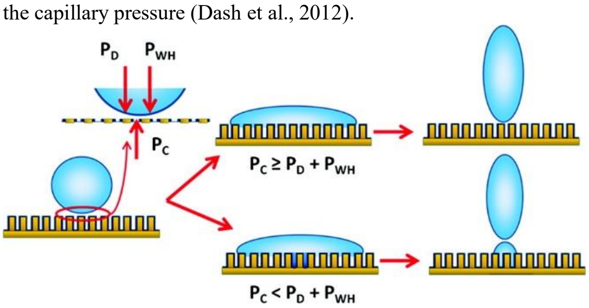

Figure 2: Schematic image showing the principle of droplet bouncing (top) versus pinning (bottom) behaviour (Dash et al., 2012).

Microstructured surfaces has no intrinsic frost repulsion and are susceptible to pinning of water droplets in the Wenzel state. Both of these aspects are fatal to the icephobicity of a surface and need to be addressed when designing an icephobic surface. As suggested by Dash et al. (2012), the pinning can be controlled by intelligent structure design that maximizes the capillary pressure. The frost repulsion is a more difficult aspect to combat. It has been demonstrated by several researchers that frost accretion is heavily dependent on the surface morphology and that microstructured surfaces do not possess the confinement needed to obtain such a behaviour.

3.1.2. Nanostructured surfaces

Nanostructured surfaces have been shown to have excellent hydrophobic properties. In addition, they have shown great potential as a basis for icephobic surface design.

He et al. (2011) investigated the frost formation on a ZnO nanostructured substrate where the surface was made up of hexagonal nanorods, seeded at random angles, grown by liquid self-assembly epitaxy and functionalized with heptadecafluoro-1,1,2,2-tetradecyl trimethoxysilane (FAS-17). They observed the formation of spherical droplets that displayed prolonged freezing times with smaller structures, implying that superhydrophobic nanostructured surfaces can significantly delay the accumulation of frost by condensation. They attributed this behaviour to a reduced heat transfer flux owing to reduced interface surface between droplet and nanorods (He et al., 2011).

Hao et al. (2014) performed a similar test using CuO nanohair functionalized with FAS-17 as well. Depending on manufacturing temperature, the surface formed in two morphologies: One fine (4-5°C) nanostructured and one exhibiting a pattern resembling flowers in a hierarchical structure 20°C). It was shown that the finer structure was able to allow condensed droplets to rise to the top of the surface as they coalesced and eventually be shed. This behaviour was retained at -5 to -10ºC but was lost at lower temperatures. At -30°C and below the condensed droplets freeze within the nanostructure and icephobicity is completely lost until reheated (Hao et al., 2014). This is to be expected as a limit of homogeneous ice nucleation presents itself in water at around -40°C (Moore and Molinero, 2011), and the exposure of the droplets to a surface will induce heterogeneous freezing and thus effectively lower the limit of supercooling i.e. raise the limiting temperature (Wilson et al., 2003).

These and other studies, have indicated that icephobicity, when discussing frost, does not only require superhydrophobicity but also specific confinement morphologies that force condensed droplets to be expelled to the surface as they coalesce. As far as structured surfaces go, this seems a plausible argument.

Zheng et al. (2011) tested a carbon nano tube film of similar length scale to the above mentioned nanostructures, with respect to shedding and freezing prevention of impacting droplets. Their results showed a clear bouncing behaviour of low impacting droplets but a reduction in effectiveness with a cold surface and supercooled water droplets. This suggests a limit below which the supercooled droplet will no longer be shed. In their article, Zheng et al. (2011) did not present any test results on the freezing of condensation but mentioned that they attempted to avoid frosting by keeping the relative humidity low. This suggests a poor repulsion of condensation, possibly due to the randomness of the nanostructure locking the condensed droplets in place and disallowing the coalescence behaviour presented by the structure presented by Hao et al. (2014). It should be noted, however, that this is conjecture.

3.1.3. Hierarchically structured surfaces

Guo et al. (2012) created samples based on the same approach as Hao et al. (2014) and He et al. (2011), as can be seen in Figure 3, but included a comparison between nano, micro and hierarchical surfaces with respect to, among other things, condensation and frost as well as freezing delay of sessile droplets. They concluded that the hierarchically structured surface was superior in all aspects and that the microstructured surface had the least beneficial effects. The reason for this superior behaviour was attributed to the lower surface exposure to the droplet, leading to significantly reduced heat transfer and thus increased freezing delay (Guo et al., 2012).

The reduced surface exposure might also have the effect of reducing the surface energy of the water droplet, pushing the heterogeneous freezing limit toward that of the homogeneous. If so, the synergistic effects might be deconvoluted by calculating the thermal energy transfer rate between the droplet and the surface with different structures.

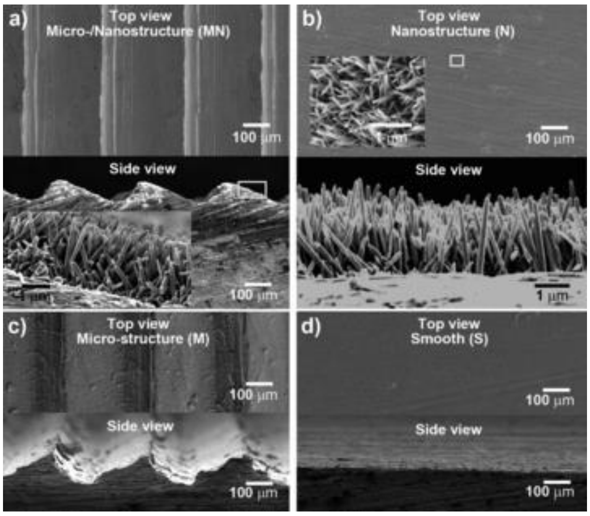

Figure 3: Overview of the nano, micro and hierarchical structures created and compared by Guo et al. (Guo et al., 2012).

Hao et al. (2014) also produced a hierarchical structure, but with somewhat different morphology (*see Figure 4*). Their hierarchical structure grew in a way that produced micro sized structures on top of the nanostructure, resembling flowers. These had a deteriorating effect on the icephobicity with respect to freezing of condensation as compared to merely a smaller nanostructure. They attributed this behaviour to the micro sized structures hindering the expulsion of condensed droplets from the nanostructure below (Hao et al., 2014).

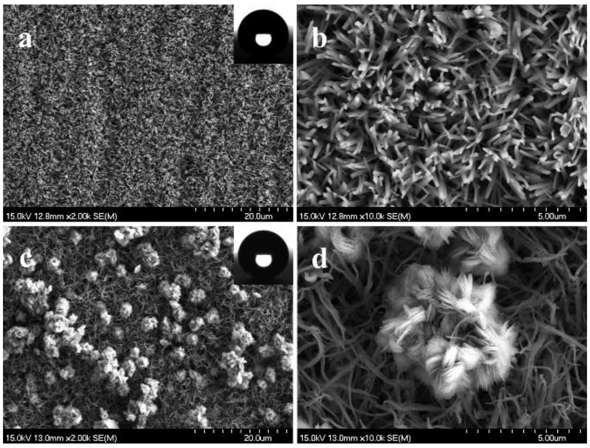

Figure 4: Hair type structures presented by Hao et al. (2014) showing nanostructures produced at lower temperature (4-5°C) (a-b), hierarchical structures produced at higher temperature (20°C) presenting the floral-type structures (c-d).

There are several designs of hierarchical surfaces. The above mentioned research is focused on a hair-like structure whereas some others use strategies like pillar-type structures (Maitra et al., 2013) or porous structures (Barthwal et al., 2013).

Barthwal et al. (2013) produced a nano-porous microstructure on alumina substrates in order to create a superhydrophobic surface with better robustness than the nano-hair or nano-pillar type surfaces. While not evaluated with respect to any icephobicity aspects, the surface did present excellent superhydrophobic properties at room temperature and is thus a good candidate for further evaluation. One crucial aspect to keep in mind in this case, however, is the behaviour with respect to frost formation. Condensation could potentially form within the structure and has the potential to damage the structure if frozen before expulsion.

Miatra et al. (2013) produced a pillar type nanostructure on a pillar microstructure in order to evaluate the potential droplet impalement resistance of such a surface. Down to a substrate temperature of -30°C, the impalement of impacting droplets was resisted for droplet velocities up to 2.6 m/s when the structural length scale was minimized. It should be noted here is that, for the case of BIPV applications, rain has a critical velocity of 9.4 m/s (Laws, 1941). At -30°C any precipitation will likely be in the form of snow, but the successful repellence at such low temperatures does suggest a possibility of optimizing the structure for rainfall using the results of Dash et al. (2012).

3.1.4. Structured coatings

Coating materials have the advantage of being easy to apply to a surface of choice and thus the potential to be an inexpensive solution, saving money on advanced manufacturing for each separate application. It is also infinitely scalable, as it can be applied to practically any surface regardless of size.

Kulinich et al. (2009) evaluated the adhesion strength of ice in relation to contact angle hysteresis (CAH) on coatings with different size particles ranging from 20 nm to 600 nm. They found that the two correlate to some undetermined degree and explain this correlation as a result of the increased surface exposure with larger CAH.

Cao et al. (2009) compared the icing of supercooled water on surfaces with silica particle composite coatings with varying particle sizes. They found a correlation between particle size and the freezing of supercooled water but argue that the critical size of particles for icing is significantly different than the critical particle size for superhydrophobicity. While the contact angle was found best for particle diameters on the order of 100nm, the minimal icing probability was found for particles with the diameter on the order of a few nm. Critical size for freezing was evaluated by theoretical calculation using classical nucleation theory.

The above coating designs are all in the micro- or nanostructure range and are likely liable to the same frost accretion problem as the structured surfaces. A promising advance in frost repulsion is seen the nanostructures produced by Hao et al. (2014) and He et al. (2011). If this behaviour can be reproduced for a coating, much has been won in the argument for the coating type solution.

While potentially cheaper and more adaptable, the coating approach limits the possibilities of having a directional structure, making the frost repulsion strategies of Hao et al. (2014) and He et al. (2011) difficult to employ. Other strategies must thus be considered in this case.

3.2. Smooth surfaces

3.2.1. Smooth coatings

Smooth coatings, or coatings that do not depend on the structure of the surface for its superhydrophobic properties, are in commercial use already today. Various kinds of fluoropolymer coatings have, in fact, been used industrially for several years, the arguably most famous of which is polytetrafluoroethylene (PTFE), also known as Teflon (DuPont™). Fluoropolymers like PTFE are intrinsically superhydrophobic and requires neither structuring nor post-treatments. Combined with low cost and versatility of application, fluoropolymers and other superhydrophobic coatings have great potential if made sufficiently icephobic and robust.

Being superhydrophobic in nature, Teflon can be expected to show a degree of water freezing delay. This was confirmed by Antonini et al. (2011) and compared to Poly(methyl methacrylate) (PMMA) which is a non-superhydrophobic polymer, as well as untreated aluminium. PMMA and untreated aluminium presented comparable results while the Teflon treated surface showed significant freezing delay as well as low ice adhesion (Antonini et al., 2011).

Smooth icephobic coatings are usually polymers of some kind and the number of polymers available is staggering. They do, however, all rely on low surface free energy, making them superhydrophobic, to imbue a level of icephobicity. The small resulting interface surface under each droplet yields a low adhesion strength of frozen droplets and low heat transfer rate. The reduced surface energy can also contribute to a lower temperature limit of supercooling as the heterogeneous freezing domain a droplet on a surface is likely to be in, is pushed closer to the homogeneous freezing domain (Wilson et al., 2003).

Smooth superhydrophobic coatings may be useful in delaying the freezing of water droplets but will eventually succumb to the accretion of ice, frost and snow. Using them by themselves is thus unlikely to be enough to attain the level of icephobicity desired for BIPV installations to steadily produce electricity all year round.

3.2.2. Lubricated smooth surfaces

While a superhydrophobic surface will be beneficial to the adhesion reduction of snow, it may counteract the sliding of snow from a tilted surface. Lubricated surfaces have the opposite effect and facilitate the shedding of snow by sliding (Kako et al., 2004). Kako et al. (2004) employed a combination of superhydrophobic and superhydrophilic surfaces in an attempt to combine the benefits of both. The superhydrophilic surfaces formed a liquid layer of water from the water contents in the snow that acted as a lubricant. This combination of surfaces resulted in a surface with sliding characteristics between the characteristics of the pure surfaces.

3.2.3. Lubricant infused surfaces

Slippery liquid infused porous surfaces (SLIPS) is a variation of a lubricant infused surface (LIS), and a relatively new type of surface. It uses a liquid layer of hydrophobic oil to attain very low ice adhesion as well as excellent frost repulsion and freezing time (Kim et al., 2012).

There are now several variations of SLIPS using varying approaches. Rykaczewski et al. (2013) used a microstructured surface combined with a perfluorinated oil. They tested this surface for frost repulsion and found frost to deplete the oil responsible for the surface's otherwise very promising icephobic attributes, within a single frosting cycle. They explained the depletion by the different surface energies leading to the oil wetting frozen droplets. When the droplets are shed, as they are supposed to, they take some of the lubricant with them, eventually depleting the surface, making it lose its icephobicity.

Duo et al. (2014) infused a microstructured surface of anodized alumina with a polyurethane-based, hygroscopic polymer that spontaneously coats itself with atmospheric moisture or even melts ice already formed. The adhesion of ice was tested at various temperatures and was found to retain substantial ice adhesion reduction down to temperatures as low as -53°C. This is very similar to work done earlier by Chen et al. (2013) (the same research group), where a similar behaviour was observed down to -28°C. Their design used a microstructured surface with a hygroscopic polymer grafted onto and into the surface (*see Figure 5*). Here too, they explained the phenomena by the formation of a liquid layer and posited that this level could be pressed further by increasing the concentration of hygroscopic polymer.

Keeping a layer of water in the liquid state down past -30°C is a significant achievement as the supercooling limit of water has been shown to be approximately -40°C in the case of homogeneous nucleation. For heterogeneous nucleation, the temperature is higher (Wilson et al., 2003). Attaining -53°C or more, might indicate that other processes could be involved. Leaching of substances from the polymer could be one explanation. This would yield a similar effect to salt on a road lowering the freezing temperature of water. This would also explain any melting of ice on the surface.

Without claiming intimate knowledge of how the polymer interacts with water, it can also be posited that the polymer might absorb water in a greater amount where the solid substructure has deeper structures. This could then lead to a selective raising of the polymer surface and thus a structuring of the polymer surface. Structuring combined with a low-adhesion material could yield some of the results reported.

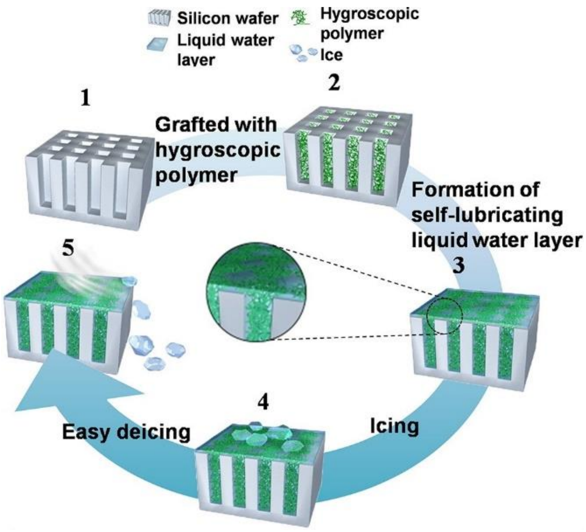

Figure 5: Conceptual image of the construction and function of the surface designed by Chen et al. (Chen et al., 2013).

Wang et al. (2011) attempted to imbue a microstructured surface with self-healing properties by creating a porous structure within the microstructure and filling it with perfluorooctyl acid. The pores acted as nano-reservoirs for the liquid, transporting it to the surface by a thermodynamic drive to minimize the surface tension.

An innovative approach that aims to combat the depletion of lubricant was presented by Zhu et al. (2013). They employed porous PDMS, infused with silicon oil that would leach out as the surface oil was degraded and depleted. While innovative and showing positive results, the strategy relies on a finite buffer of lubricant and thus might not be the best approach for BIPV applications.

SLIPS and LIS surfaces have numerous variations and hold great promise as icephobic surfaces. The technology is, however, immature still and requires further research before any application is released on the market. For BIPV, it has several advantages that make it very interesting, not the least of which is the potential to employ a translucent oil to a translucent substrate.

Other important possibilities for BIPV applications include tuning the composition and thickness of the liquid layer. This could yield positive effects to anti-reflection and colouration by selective reflection and interference in the liquid, and angular shading (to hide a solar cell in certain angles) by tuning the translucency itself.

3.3. Other strategies

An exciting and very recent development by Irajizad et al. (2016) employ a ferromagnetic liquid to combine the low liquid-liquid interface energy of the SLIPS approach with a magnetically controlled structured surface. This creates a surface that is structured by the magnetic field but otherwise molecularly smooth as can be seen in the Figure 6. Unlike the normal SLIPS, the magnetic slippery surface (MAGSS) liquid layer is here secured in place by both structuring of the solid sub-surface as well as the magnetic field. The integrity of the liquid layer is tested with promising results and the surface is reported to yield outstanding results in freezing time delay, ice adhesion and mobility (Irajizad et al., 2016).

The outstanding icephobicity results are, no doubt, a result of combining the low adhesion of a SLIPS layer with texturing, allowing for a low adhesion layer to only adhere to ice and snow on a fraction of the surface. While new and relatively unexplored, this approach to surface design allows for a unique texturing versatility. If properly designed, one could imagine a tuneable magnetic field that could be varied to physically shake of snow and ice or even use rolling waves to move the snow and ice along the surface to facilitate shedding in extreme weather.

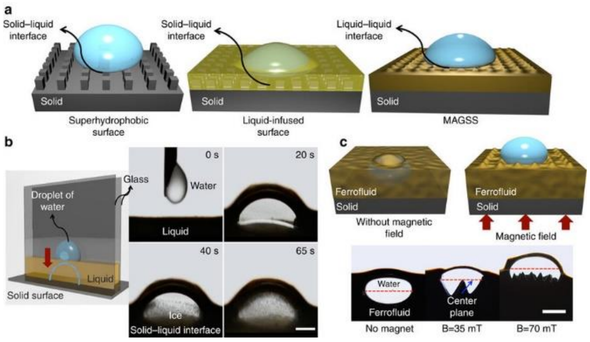

Figure 6: The formation of liquid-liquid interface on a MAGSS. (a) The difference between structured surfaces, an ordinary SLIPS surface and the MAGSS surface. (b) The penetration of water in the oil as shown with a Hele-Shaw cell. (c) The droplet rising from the ferrofluid with applied magnetic field. Reproduced from Irajizad et al. (Irajizad et al., 2016).

4. Building integration of photovoltaics

4.1. Opportunities and benefits

Integrated photovoltaic panels allow us, not only to have an aesthetically pleasing building, but also allow for buildings to be architecturally designed to optimize the shedding of snow and ice. Snow, especially, can be difficult to remove if there is not enough physical space for the snow to fall away when successfully shed by the surface. An example of this can be seen in Figure 7.

Figure 7: Example of non-integrated, traditional photovoltaic panels placed without regard for snow removal on the roof of Block 4 of Powerhouse Kjørbo (Norway) (Ødegården, 2016).

Integration into façades have the greatest shedding potential as it is perfectly vertical but even a slight angle from the horizontal would be beneficial to the removal of ice and snow. The smallest angle for each surface treatment/design could conceivably be calculated based on icephobicity experiments for ice shedding, and a standard could be developed that takes the roof or façade design into account. The same calculations could be done for snow as well and would not necessarily be the same as for ice. In future architectural designs, software could make recommendations to surface treatments that optimize these factors to obtain the best possible shedding of snow and ice.

4.2. Challenges

If the successful design implemented in a commercial product requires continuous support and service of surface treatments or similar, the placement of the BIPV will be of utmost importance. A roof BIPV installation on a tall building would present a hazard and a significant threshold for maintenance. The same would be the case for a façade of BIPVs at great heights. A design that is as robust as possible is therefore desirable. This does not, however, disqualify any surface that needs some maintenance. Several attempts have been made at self-healing surfaces and the entire group of SLIPS have the potential to be self-healing.

The surface must also be able to handle challenges unique to PV installations. Leaves falling must not stick to the surface, bird droppings must be cleaned off, twigs and other solid objects must not damage the surface to any great extent and so on. Making a surface self-cleaning while physically robust is thus a very desirable and challenging goal.

If a building is designed with BIPV installation taken into serious consideration, it must be placed in a way that optimizes the exposure to solar radiation. If possible, it should also be optimized for natural cleaning effects like high wind shear and take into account, e.g. the falling of leaves in autumn. A cost effective, self-cleaning, icephobic, self-healing, robust surface can only go so far on its own.

5. Production

The production of superhydrophobic surfaces in quantities and sizes required for general application to various surfaces, put serious demands on the cost efficiency and scalability of the methodology.

When it comes to BIPV applications, the area of each module is relatively small, as compared to applications on aircraft or ship hulls. It can be performed in a controlled environment and in several parallel processes. This reduces the need for large area application.

Coatings of varying kinds are by far the most versatile applications. They can be applied by users of already installed, traditional solar panels as well as factory made state-of-the-art BIPV panels.

Structuring is a slower process that requires some specialized equipment, but is still scalable in a factory setting. Methods include etching techniques, epitaxial growth and structured coatings that may be applied as any other coating. Possibly with the need for heat treatments depending on the specific coating.

SLIPS and LIS are combinations of the two designs. Structuring by etching is common practice in processor manufacturing and coating can be as simple as an oil bath. The new addition of MAGSS to the SLIPS family will likely require some innovation and further development. Sintering of magnetic powders could be a potential way of constructing a selectively magnetic structure.

6. Future research opportunities

Icephobic surfaces require multidisciplinary studies and is a relatively new field. As such, the research is spread in all directions depending on applications. It would therefore make sense to define a series of tests that encompass most, if not all, of the aspects of icephobicity. Ice adhesion, snow sliding, frost formation, freezing time delay, pinning, depletion, cycling and so on. This would also open the door for a better definition of what is and is not an icephobic surface.

Another aspect that appears a natural evolution of this field, is a model for predicting pinning behaviour by structured surfaces. Dash et al. (2012) calculated a critical velocity, above which pinning would occur, for their structure based on capillary pressures. This method could possibly be applied to a general case and thus yield a confinement constraint on microstructured surfaces.

In the area of BIPV and other weather exposed surfaces, it could be possible to establish how ice adhesion relates to snow adhesion. It could also be of interest to attempt research into how snow settles on a surface depending on quality and circumstances.

Snow is rarely reported on with respect to passive repulsion. This could be a symptom of the difficulty in creating controlled experiments or possibly a lesser perceived urgency than other forms of icephobicity. It is, however, nonetheless important in the instance of BIPVs, where snow hampers production quite effectively.

In the pursuit of an icephobic surface material, there is surprisingly little published that includes the freezing dynamics of water. How homogeneous nucleation relates to heterogeneous nucleation and how the various surfaces can be expected to behave from a thermodynamic perspective.

For the BIPV specific research, it might be of interest how a small community of BIPV powered houses would handle snow and ice accretion. Some houses might have more beneficial conditions and thus contribute more to a smart local grid.

MAGSS is a promising new concept that deserve some further attention to determine the potential in all snow- and icephobic aspects. It would also be of interest to experiment with active magnetic grids to create physical motion, moving or shaking the surface to loosen any snow or ice accretion.

7. Concluding remarks

In this review, all indications point to superhydrophobicity not being the whole answer but rather an important piece of the puzzle to obtain a truly icephobic and snowphobic surface. Additionally, it needs to be able to ward off several kinds of snow and ice as well as frost. It also needs to be robust enough to withstand the rigors of harsh weather and, in the case of building integrated photovoltaics (BIPV) applications, it needs to have a longevity of up to 25 years.

Few of the discussed surfaces are made in a way that can be directly applied to BIPV with respect to optical transmittance. They are, however, excellent proofs that there is potential for a passively snow and ice free roof, clad in BIPV panels.

The icephobicity of BIPV solutions could be viewed as a balance between the icephobicity of the surface and the BIPV integration architecture. Ice and snow must not only be repelled by the surface of the BIPV, but also removed in an effective manner from the building so as to not cause build-up at inconvenient locations.

In the pursuit of icephobic surfaces, it is easy to only look at the benefits of the material characteristics and forget about the surrounding environment. Use of biodegradable oils in slippery liquid infused porous surfaces (SLIPS), taking the potential health effects of nanoparticles into account and looking at the suggested product as a whole, are important factors not to neglect. What world are we leaving behind and what materials and substances would I let my kids near?

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