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Per-Olof Andersson Borrebæk

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Thesis for the Degree of Philosophiae Doctor
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Department of Civil and Environmental Engineering

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Foreword

When I started my research in snow and ice adhesion mitigation, the subject matter appeared so large and so incomprehensibly complex; nearly impossible to grasp in its entirety. From there the field appeared to grow with my capacity to ask more specific questions, until I simply had to pick one narrow sliver to make my own.

Snow is a fascinating field of research and, in the context of improving the applicability of solar energy in cold regions, it feels especially motivating as I may contribute to a development of society towards a better future. A better future in the sense that coming generations may find a more intelligently designed way of life; a way that allows them to live modern, comfortable lives while in balance with their environment.

To this end photovoltaics (PV) offer a spectacular opportunity to harvest energy for our very energy-hungry society, directly from the sun, without having to take the extra steps through complex planetary chemistry. Modern homes often have PV installed on the roof, hanging on brackets or braces outside the roof itself. This adds an environmentally redundant layer to the building envelope. Having the PV modules replace the roofing is thus the next logical step in PV module design.

Building integrated photovoltaics (BIPV) is a fairly new technology that has seen some sudden rises and falls in popularity as new and exciting products have been announced. Such PV modules may replace roof elements, wall elements, or even replace roads, pavements and parking spaces. PV may thus be integrated, not only directly integrated into buildings, but the surrounding infrastructure as well.

In northern climates, snow and ice present a significant challenge as they may cover the BIPV installation and thus reduce power production significantly during the part of the year when the energy is most needed. The project of which this research was part, was started in response to a growing need for knowledge of how to approach solar energy in Norway; a country where snow and ice are very prevalent through significant parts of the year.

It is my sincere hope that solar energy replaces and revolutionizes the manner in which we generate our energy. This thesis represents my tiny contribution to this vision, so far.

Per-Olof Andersson Borrebæk

Trondheim, April 2020

Acknowledgements

This thesis research has been produced under the project *Building Integrated Photovoltaics for Norway* (BIPV Norway), supported by the Research Council of Norway and several partners. I'd like to thank the partners of this project for their support and input throughout.

Among these partners, Dr. Erik Stensrud Marstein and Dr. Josefine Selj from the Institute for Energy Research (IFE), and Morten Gaustad from Getek A/S deserve a special mention for their unwavering support and aid in my work.

Throughout this project I have had the privilege to have three fantastic supervisors to show me the ropes and mold me into a proper scientist. My main supervisor, Prof. Bjørn Petter Jelle, with his extensive knowledge of publication culture and endless pool of anecdotes, has been instrumental in my understanding of academic research and has shown me the way through the forest of written and unwritten rules involved in academic research and publication. Prof. Zhiliang Zhang, one of the most collected and insightful researchers I have ever met, has been a constant in a world of variables and can always be counted on to place a disorganized bundle of thoughts into a proper context. Prof. Alex Klein-Paste, the most clear-minded realist and superb experimentalist I have ever had the pleasure to know, has aided me in cutting away that which does not belong and focus only on the things that really matter.

I would like to extend a special thanks to Dr. Elena Scibilia for her support when things were tough. She was a beacon of light when I was falling in the darkness.

Lastly, but perhaps most of all, I'd like to thank my very supportive wife, Live Andersson Borrebæk, for bearing the lion's share of the daily burdens so that I have been able to work. I dedicate this thesis to her and our fantastic son, Tristan.

Summary

Solar energy is one of the main environmentally responsible forms of energy production and one that is very interesting for private citizens to invest in. The cost for private citizens to invest in solar energy, however, has still not reached parity with fossil fuels such as natural gas. Integration of photovoltaic cells in building skin elements such as roofing or wall cladding, however, makes it possible to co-invest in both simultaneously. This may allow for a dramatic energy price reduction while maintaining the original aesthetics of the architecture.

In the cold regions of the world, where snow and ice are common occurrences, these present another challenge by accreting on the solar panels. The winter months, when snow and ice is most prevalent, is also the time when the energy is most needed. Though it is the least productive time of the year, between 1-20% of the annual production may be lost due to accumulation of ice and snow covering the solar panels.

Based on a thorough state-of-the-art analysis, resulting in two review articles, it was determined that snow adhesion differs fundamentally from ice adhesion. Snow adhesion is a less explored area, often conflated with ice adhesion. The scope of this thesis was therefore narrowed from including both ice and snow adhesion mitigation, to focus specifically the mitigation of snow adhesion.

In order to explicitly test the similarities and differences between ice adhesion and snow adhesion, a controlled method for snow adhesion measurement was developed. This method was then applied to known ice adhesion mitigating surfaces to ascertain the extent of the difference in behavioural trends. It was found that the level of ice adhesion mitigation has no apparent bearing on the level of snow adhesion.

The method was further applied to glass surfaces of varying roughness to begin the process of accumulating quantitative adhesion data specific to snow, and to test the limitations of the method. Results indicate that increased surface roughness on glass in the micrometre scale will have a drastic negative impact on snow adhesion mitigating efforts.

All analyses of snow adhesion were performed using synthetic snow. The use of synthetic snow allows for repeated production of snow with identical properties, something that cannot be attained with *in-situ* measurements using natural snow. This ensures the reproducibility of the experiments such that results may be independently verified.

After having determined that snow adhesion should indeed be studied separately from ice adhesion, a suggestion for a redefined terminology was presented, along with a framework for classification of performance.

Dedicated to Live and Tristan, around whom my universe revolves.

Nomenclature

The following nomenclature has been used throughout this thesis. Brief explanations of these and other concepts and definitions can be found in Appendix C.

AFM – Atomic force microscope

BIPV – Building integrated photovoltaics

BWI – Bulk water ice

CA – Contact angle

CAH – Contact angle hysteresis

CIP – Crack initiation and propagation

IFM – Infinite focus microscope

IP – Ingress protocol

LIT – Low interfacial toughness

LLL – Liquid-like layer

LWC – Liquid water content

MSI – Mullin-Sekerka instability

PV – Photovoltaics

RH – Relative humidity

ROI – Return on investment

SLIPS – Slippery lubricant impregnated porous surface

List of publications

Articles

Part 1 – Review of the field and identification of knowledge gaps

I. Passive snow repulsion: A state of the art review illumination research gaps and possibilities (*Published*)
II. Avoiding Snow and Ice Accretion on Building Integrated Photovoltaics – Challenges, Strategies, and Opportunities (*Published*)

Part 2 – Development of an experimental method

III. A gravity-based method for snow adhesion measurement (*Submitted for publication*)

Part 3 – Surface development

IV. Snow adhesion on icephobic surfaces (*Submitted for publication*)
V. Influence of glass surface roughness in the micrometre range on snow adhesion (*Submitted for publication*)

Part 4 – Introduction of a new classification and terminology

VI. A framework for classification of snow- and icephobicity (*Submitted for publication*)

Datasets

I. Snow sample aspect ratio influence on snow adhesion data from tilting table experiments. (*Published*)
II. Snow adhesion data from icephobic surfaces. (*Published*)
III. Surface roughness impact on snow adhesion. (*Published*)

Contents

Introduction

1 Introduction

Renewable energy generation is a hot topic around the world as global warming becomes an ever more present theme, permeating a wide variety of fields. The most common renewable energy forms, wind and solar energy, both see heavy investment. In cold regions, where abundant snow and ice accumulation is a challenge, certain precautions and special solutions have to be employed to keep snow from blocking solar panels. The research presented in this thesis is focused on the matter of mitigating the impact of snow on building integrated photovoltaics (BIPV).

1.1 Traditional building mounted photovoltaics

Photovoltaic (PV) modules have been mounted on buildings for many years and, as one might expect, often on the roof as the angle often corresponds approximately to the optimal angle for PV energy generation. Larger installations are commonly found on the flat roofs of industrial buildings, where PV modules are placed on a frame to angle them as closely as possible to optimize annual solar exposure.

Many larger PV installations are mounted on rigs standing on the ground, covering large areas. Such practices claim significant land areas to produce relatively little energy. By instead placing PV on buildings, the land use can be combined for both habitation or productivity, and energy harvesting. Using roof space for PV often also allows for utilization of otherwise unused space, of which cities and other densely built regions have an abundance.

1.2 Building integrated photovoltaics (BIPV)

Placing a layer of PV on top of the intended outer skin element of buildings, makes for a redundant extra layer of cladding. While common PV modules do not commonly meet the same requirements as traditional building skin elements, they do form an extra cladding layer that could be made to form a proper building skin. PV that do meet these requirements are known as *building integrated photovoltaics* (BIPV).

1.2.1 Integration alternatives

Most commonly, PV is mounted on roofs as they are commonly angled in a way that is closer to the optimal angle (perpendicular to the incident light) than other surfaces. As the roof cladding is not usually implemented as a water-tight building membrane, making roofing tiles or modules that behave similarly to traditional roofing tiles is perhaps not as complicated as it may first appear.

The standardization of cladding element size dictates the optimal module size or sizes that may be used. Opting to disregard such standardization may incur extra cost of sub-structure design to properly support the modules. In addition to this, the only actual requirements for building cladding elements is that they function as intended. They have to repel most precipitation and act as a shield against the elements, while being securely fastened and the substructure allowed to dry out any accumulated moisture.

The BIPV modules themselves, much like traditional PV, must be properly weather resistant to deter water ingress that may damage the electrical components. Other than that, they must comply with regulations concerning electrical installations (particularly including fire safety), which may differ between countries or even regions within a country.

Several studies have shown that proper use of albedo (reflection of solar radiation) effects from snow or bodies of water, may allow for drastic increases in PV energy production [1–3]. This makes façade elements well suited for certain environments, but site-specific considerations must be taken into account for each project.

Shading products are sometimes considered integrated and lend themselves well to PV energy production as their inherent function is to reduce solar radiation transmission into the building. As they are not integral parts of a buildings protective skin, there are generally no building code requirements beyond common safety aspects.

1.2.2 Cost reduction

In addition to eliminating an otherwise redundant building element, lowering the complexity of the building skin, building integration allows the price of photovoltaics to be offset by the price of roof or façade cladding. While manufacturers may aim to produce BIPV at prices on par with traditional cladding, one should still expect an added cost relative to traditional cladding elements. Continuous energy production, however, allows some of the cost to be compensated for, ideally yielding a net cheaper building cladding.

A traditional building skin has a long lifecycle. Typically, around 40-50 years can be estimated for a roof [4] and approximately the same for a façade [5]. Ideally, the PV energy generation should remain unchanged from installation to the technical end-of-life of the element, but realistically one should assume a loss of efficiency of about 1% per year, tapering off to around 50% after 25 years [6]. Both the lifetime energy production and the estimated technical lifecycle of the BIPV element have to be considered when regarding the total cost of a building cladding element, with or without integrated PV.

1.3 The challenge of ice and snow

In cold regions, such as high latitudes or altitudes, cold precipitation such as snow and ice, regularly accrete and can cause photovoltaics to lose as much as 20% of the annual potential production, depending on location [7,8]. Local variations can be extreme but most locations with recurring snowfall can be expected to lose around 1-10% of the annual production [7].

The production losses directly resulting from accretion of snow and ice have been estimated between 1-12% [8,9]. In locations with heavy snowfall there may thus be a significant impact on the return on investment (ROI) that may prevent investments in such systems.

Ice adhesion is the most commonly researched facet of cold precipitation impact mitigation. Surfaces that can passively lower ice adhesion significantly are often called *icephobic*, which has also come to include the mitigation of ice accretion and snow adhesion. As shown in the research presented herein, this is incorrect.

1.4 Research objective and scope

Mitigating the problem with ice and snow accumulation is a complex matter that has been reviewed in Articles I and II. These serve to structure and clarify terms and concepts, and to reveal trends in successful surface designs.

Originally, the scope of this thesis was to include the mitigation of both ice and snow, based on the assumption that ice adhesion and snow adhesion could be mitigated in the same manner. This assumption has been tested and shown incorrect, motivating a shift of focus towards snow adhesion mitigation specifically. Ice accretion may, naturally, influence the adhesion of snow but, for this research, the scope has been limited to snow adhesion and its possible mitigation. In moderately cold climates, snow is also the most common challenge presented by cold precipitation.

The overarching objective of this thesis is to find ways in which the impact of snow on BIPV annual production may be mitigated through intelligent surface design. In essence, surface design which permits low snow adhesion. To this end, the following research questions have been posed:

- How well does snow adhesion correlate to ice adhesion?
- How do we test and measure snow adhesion?
- What surface design aspects are important to minimize snow adhesion?

It has previously been suggested that different types of PV modules and methods of PV implementations (i.e. fastening method, use of frames, etc.) may impact the accumulation of ice and snow [10]. In this thesis, the type of PV or BIPV technology and the method of implementation has been largely excluded in order to focus more specifically on the adhesion aspect.

Background

2 Background

A thorough review of the field has resulted in two state-of-the-art review articles (Articles I and II). The following chapter is not an exhaustive description, but rather a recapitulation of some of the most important points for the present context.

2.1 Formation and ageing of snow and ice

Understanding the different processes by which ice and snow form in nature is vital to the understanding of the mitigation of these phenomena. Though they are variations of the solidified water, their origin and how they behave over time fundamentally impact their observable behaviour.

2.1.1 Formation of ice

The water molecules of any body of liquid water move in a random pattern, bumping into each other and everything around them, by virtue of thermal energy. Statistically, such random motion will always yield localized areas with a high density of molecules that have a small attraction to one another. At temperatures above the melting temperature, however, the kinetic energy of each molecule easily overcome the attraction and the local minima are quickly lost, only to form elsewhere [11].

Ice can form when the temperature of the liquid water reaches below the melting point. At the pressure of one atmosphere (earth sea level), this generally occurs at 0°C, below which, the kinetic energy may not be able to overcome the random fluctuations in density, and they instead begin to agglomerate. These initial agglomerates are known as ice embryos.

The growth or dissolution of an ice embryo can be described by thermodynamics through considering the transition of a system from one state to another: One of single-phase liquid water (state A), and another with an ice embryo within the liquid phase (state B). The Gibbs free energy of state A can be described as

$$G_A^\alpha = \mu_A^\alpha N \tag{1}$$

and for state B as

$$G_B^{\alpha+\beta} = \mu_B^\alpha N^\alpha + \mu_B^\beta N^\beta + \gamma A \tag{2}$$

where μ is the bulk chemical potential, N is the number of molecules, A is the embryo surface area and γ is the energy per-surface-area-unit of the interface. For chemical potentials, the only influencing factors are temperature and pressure and, assuming these are equal in A and B, it thus holds that $\mu_A = \mu_B = \mu$. This allows for formulation of the transition as

$$\begin{aligned} \Delta G &= G_B^{\alpha+\beta} - G_A^\alpha = \\ &= \mu^\alpha N^\alpha + \mu^\beta N^\beta + \gamma A - \mu^\alpha\left(N^\alpha + N^\beta\right) = \\ &= \Delta\mu N^\beta + \gamma A \end{aligned} \tag{3}$$

where $\Delta\mu = \mu^\beta - \mu^\alpha$. Using $N = \varrho V$, where ϱ is the number density, this may be expressed as

$$\Delta G = \Delta\mu\rho^\beta V^\beta + \gamma A \tag{4}$$

Since the beta is the more stable phase (smaller chemical potential) below the melting temperature, $\Delta\mu$ will be negative. If the approximation of a spherical embryo is made, the area term will initially grow faster than the volumetric term, creating an energy maximum at a critical radius, *r*, as seen illustrated in Figure 2.1. Above this radius, the addition of more molecules will lower the total energy and the embryo keeps growing. If the critical radius is not reached, the embryo will dissolve [12].

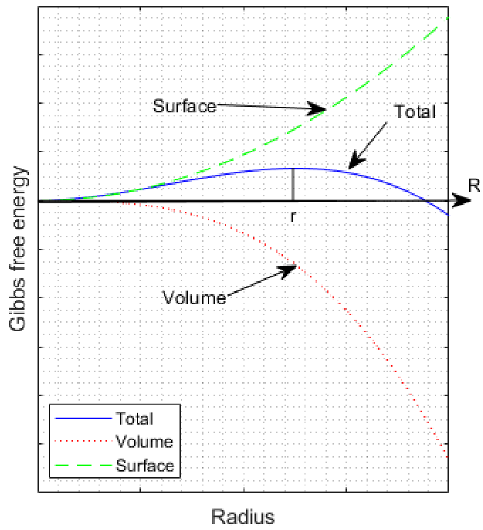

Figure 2.1: Gibbs free energy as a function of ice embryo radius. The critical radius for continued growth is here noted as *r*.

This process of freezing, known as classical nucleation theory, is the most common way to describe the solidification process of a liquid. Despite the arguable error in its description of a microscopic system, using bulk thermodynamic properties, it works well as an estimation in the present setting.

Classical nucleation theory may also be extended to include an interface such as that between water and a contaminant or the interface between a water droplet and air. This introduction alters the energy relation described in equation 4 and a new term is introduced

$$\Delta G = \Delta\mu\rho^{\beta}V^{\beta} + \gamma_{\alpha\beta}A_{\alpha\beta} + (\gamma_{\beta\delta} - \gamma_{\alpha\delta})A_{\beta\delta} \tag{5}$$

where the index, δ, represents the new phase [13,14]. Here, we can see that, the larger the interfacial energy between water and the external phase, the more acute the influence of the third phase will be on nucleation.

2.1.1.1 Melting point suppression

The surface curvature of an object has important implications. The Gibbs-Thompson effect describes a pressure increase within objects with high curvature surfaces, which translate to a temperature increase and may be interpreted as a suppression of the melting point [12]. This implies that the temperature of a small enough droplet can have a significantly lower melting point than the bulk material.

A rain drop only experiences a very small effect of the curvature and the internal temperature may only increase by a fraction of a degree. In order to reach a melting point suppressed to -10°C, the droplet radius would have to be reduced to the order of a few nanometres [15,16]. This will be shown to be relevant in the suppression of ice accretion through frost formation.

2.1.1.2 Supercooling

If a droplet of water does not have a seed particle (i.e. a dust particle or other contaminant) that lowers the critical radius, *r*, it can remain in its liquid state far below its melting point. This is known as supercooling and occurs regularly in nature as supercooled rain. When supercooled droplets hit a surface, the metastable state of supercooled droplets is perturbed and the water freezes on impact. When this occurs, glaze ice is formed.

2.1.2 Formation of snow

Snow crystals are single crystal formations of ice and can be formed from any ice crystal symmetry. There are 13 known possible symmetries [17] and of these, the hexagonal (I_h) is the most studied as this is the most stable form under natural terrestrial conditions. Snowflakes, as we see them fall in wintertime, are commonly agglomerations of multiple such ice crystals and form large, fluffy, three-dimensional shapes [18].

Snow crystals form in the atmosphere by the condensation and solidification of water vapour [19]. They are commonly known for their intricate hexagonal, symmetrical pattern that occurs with great variation. So great, in fact, that they are often said to all be unique. The validity of this common claim will not be discussed here, however, the morphology of snow crystals has been categorized in a multitude of studies over the years [18,20,21] including a formal classification scheme [22].

The formation process of a snow crystal begins with the condensation of a few water molecules, often on a dust grain that lowers the energy barrier for ice nucleation. As more water molecules condensate and adsorb to the tiny ice crystal, the crystal grows and form hexagonal plates by the stabile phase's hexagonal crystal symmetry.

At a certain diameter, nascent ice particle begins to grow from the six corners. This generates a larger surface area to volume ratio, apparently in conflict with the commonly accepted notion that surface area is always reduced in nature due to minimization of energy. In 1963, Mullins and Sekerka [23] showed analytically that a small perturbation, simulated by a harmonic oscillator, on a spherical particle would preferentially grow in certain size ranges compared the particle itself. This means that their simulated perturbation would grow for particle radii larger than a certain value. This is known as Mullins-Sekerka instability (MSI), as it is argued that the spherical particle will be unstable for all radii where growth of the perturbation occurs.

MSI, however, does not provide a complete picture. It assumes very small perturbations and ignores internal mass diffusion processes while disregarding attachment kinetics. Libbrecht [24] has presented an explanation wherein he argues that, while MSI initiates branching, attachment kinetics and diffusion limitation are responsible for the growth. He argues that, the Berg effect (the elevated concentration of vaporized molecules above a convex surface) is responsible for elevated attachment rates near the edges of a prism. In slow growth, the attached molecules are allowed to diffuse away from the edge. At higher growth rates, the directional difference in attachment rate makes the crystal grow preferentially in one direction. He calls this the edge-sharpening instability [24].

The precise growth kinetics of snowflakes are exceedingly complex. The general process, however, is conceptually important for the understanding of the ageing process of snow. This in turn is important for the understanding of the adhesion of accumulated snow.

2.1.2.1 Wet and dry snow

Snow under ordinary terrestrial conditions, practically always contain some amount of liquid water, usually referred to as its *liquid water content* (LWC). Despite the LWC being a continuum depending on temperature and pressure, snow is commonly referred to as either *wet* or *dry*. These have been cited to be defined by the temperatures -1°C and -2°C where warmer than -1°C yields wet snow and colder than -2°C yields dry snow [25,26]. This definition stems from a dramatic shift in measured LWC in this region.

2.1.2.2 Hail and graupel

Hail forms as tiny ice embryos, much like snow, but is subjected to warm updrafts that keep them airborne and with sufficient heat to form ice closer to its equilibrium state [27]. Depending on conditions, hail can range in size from millimetres to centimetres but are generally round or oval in shape. Graupel forms as ice aggregates onto snow and ice crystals in the atmosphere, forming more complex and solid structures [28]. Graupel pellets are more porous than hail stones but may otherwise look similar and are often mistaken for hail.

2.1.3 Ageing of snow

The well-known dendritic snow crystal is, as previously discussed, formed by rapid growth in an unstable morphology with limited diffusion rates to counteract it. In essence, the water molecules do not have enough time to move into the most thermodynamically stable positions. After the growth has seized, the diffusion processes continue. Even at sub-freezing temperatures, the crystal morphology changes slowly from the dendritic towards the hexagonal prisms (or spherical crystals in the limit) through the Gibbs-Thompson effect. This is process is often referred to as metamorphosis of snow.

In contact with other snowflakes, diffusion of molecules will occur between the snowflakes as well. When this occurs, the molecules are deposited at, or near, the contact points and the particles begin to coalesce. The phenomena, known as sintering, is a process driven by the surface area reduction that lowers the potential energy of the system [29–32].

In the simplest case, sintering occurs between two spherical particles. The convex curvature of the particles increases the internal pressure of the particles just below the surface, while also raising the vapour pressure just above the surface [12]. The increased pressure will then drive diffusion processes that transport molecules or atoms towards the contact point (or neck) where the concave curvature has the opposite effect, resulting in a lowered pressure.

Six individual diffusion processes, schematically presented in Figure 2.2, can be argued to play a role in the sintering process: (i) Surface diffusion, (ii) lattice diffusion from surface, (iii) vapour diffusion from surface, (iv) grain boundary diffusion, (v) grain boundary lattice diffusion, and (vi) dislocation lattice diffusion [33–36]. While diffusion rates of all kinds of diffusion are heavily temperature dependent, the processes never come to a complete halt.

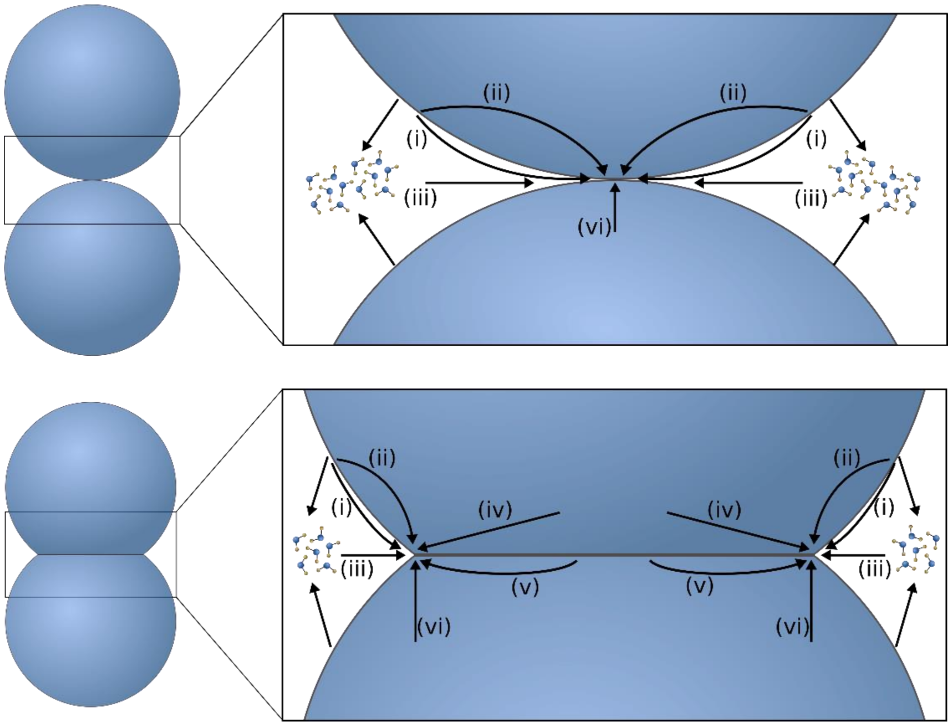

Figure 2.2: Schematic of sintering processes present at point contact (top) and after neck formation (bottom), interpreted from equations and descriptions by German [34].

In the case of snow, there is a multitude of highly curved features. The convex dendrite needle ends are complemented by a large number of concave contact points between the dendrite arms. So long as there are curvature differences present, the process continues and, eventually, the diffusion processes rounds the snow crystal features to form hexagonal prisms or plates, depending on the ambient temperature [24]. Given sufficient time, spherical particles are formed, though this process is very slow.

The decay of a snowflake (rounding of features) is a slow process at non-melting conditions. Given infinite time, however, the equilibrium shape of the crystal, where the surface energy is at a minimum, will be spherical. The full equilibrium shape, though, has apparently never been confidently recorded, owing to the near infinite time required to reach such a state [19]. Colbeck, however, claims the process is only this slow under the condition that no temperature gradient is present, a state only found in laboratory conditions. In nature, where a temperature gradient is practically always present, the process is significantly faster. The decay of a snow crystal under laboratory conditions is illustrated in Figure 2.3 [37], and is simplified in Figure 2.4 with indications for matter transport through diffusion (i.e. how the metamorphosis transpires).

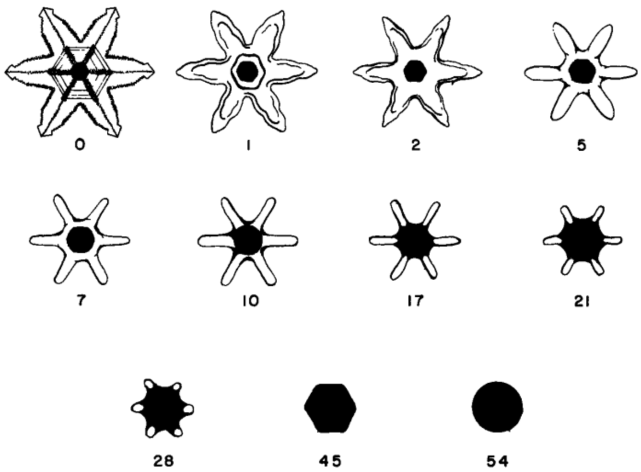

Figure 2.3: Decay of a snow crystal towards the equilibrium shape [37].

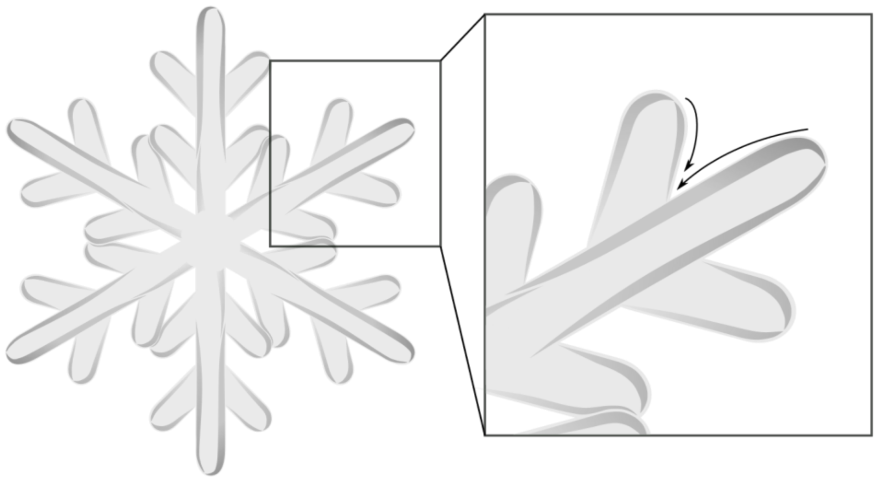

Figure 2.4: Simplified and exaggerated representation of a snow crystal with directional indication for diffusive transport.

2.1.4 Formation of frost

Frost is a type of low-density ice formation that forms through either freezing of compensated water droplets or through desublimation (i.e. gas to solid phase transition). The precise physics of this will not be addressed here but the process shares some features with the formation of snow.

Frost can form in a variety of geometries and sizes depending on the conditions and path of formation. Generally, frost is separated in hard rime, soft rime, and hoar frost. Hard and soft rime form in the same manner, but under different conditions leading to different crystal structures and, thus, different overall densities. This has given rise to their names. Hard rime is generally smaller crystals that are more closely packed while soft rime consists of larger crystals that are often the result of strong winds. Soft rime is therefore generally attached to the leeward side of branches and other objects and stretches in the wind-ward direction.

Hoar frost differs from these in that it forms on snow crystals, either on the surface (i.e. surface hoar) or under the surface (i.e. depth hoar) [22,37]. It is also very dependent on diffusion rates of moisture within snow and thus on the incident solar radiation [37–39].

2.2 Interfacial mechanics

The interfacial mechanisms, her understood as adhesion and release mechanisms, are believed to be the physical root of the adhesion mitigation problem. They will here be mentioned and described very briefly, to provide a contextual understanding only.

2.2.1 Adhesion mechanisms

Adhesion is generally understood as the force per area unit required to separate two surfaces. In the case of a dry interface of solids being separated by shear forces, this is referred to as friction. With the inclusion of a liquid, however, or as in the case of ice, a liquid-like layer (LLL), an adhesive contact is formed. Whereas dry friction may be described by a linear relationship between the normal force on the interface and the lateral force required to shear the interface, adhesion such as that provided by a liquid cannot be described in this way. This is therefore called *lateral adhesion* and is in this thesis described simply as *adhesion*.

Most generally, adhesion of snow or ice is measured by the application of a lateral force to a sample in contact with a substrate material. As it would be exceedingly difficult to separate the dry static friction from the adhesion, the two are accepted as a total adhesion though different processes govern the two.

Static friction is often regarded as the overcoming of mechanically interlocking of surface asperities, in addition to adhesive forces at each contact point. In the present context, this becomes an aspect of the lateral adhesion. In addition, the liquid or LLL interface creates molecular adhesion through the formation of, primarily, hydrogen bonds.

2.2.2 Interfacial release mechanisms

Release mechanisms can be understood as the process by which the adhesion mechanisms are overcome. While ice, snow, and liquid water all adhere strongly thorough formation of hydrogen bonds, liquid water behaves mechanically different when a mechanical force is applied. A droplet may roll or slid away, in a complex dance of forming and disrupting bonds due to the mobility of the molecules. Ice and snow, however, have only a limited number of free (LWC) or semi-free (LLL) water molecules, making other effects visible. E.g. solid ice can allow for crack initiation and propagation (CIP) at the interface, which can be described as a cascade failure of interfacial bonds. Snow does not allow for this as it is dependent on the stiffness of the material, or its ability to distribute force within itself [40]. Furthermore, the discontinuity of the interface forces the crack initiation to occur repeatedly, a more energy intensive process than the mere propagation of an existing crack.

A recent discovery by Golovin et al. [41] indicate that there may be more to the story, however. They introduced the concept of low interfacial toughness (LIT) to describe the observed effect of ice adhesion for large scale interfaces. Their results indicate that making polymeric coatings thinner and harder has the potential to drastically decrease interfacial toughness and reduce the force required for shedding.

A surface designing for ice adhesion mitigation by CIP thus has no beneficial effect for snow, as the snow cannot distribute mechanical strain within the material. This is corroborated by the results in Article IV. The impact of a LIT material on snow is thus far unknown, though given the relatively low Young's modulus of snow compared to ice, mathematical descriptions of interfacial toughness presented by Golovin et al. [41] indicate that the interfacial toughness may be expected to be high. It is therefore reasonable to conclude that surfaces need to be designed specifically for one or more types of cold precipitation needed for the intended application.

2.3 Management systems

There are several strategies for dealing with ice and snow, ranging from shovelling snow to burning ice away with blowtorches from train tracks [18]. Here we view them as active or passive depending on their consumption of energy to perform their task or not.

2.3.1 Active management systems

The most common systems are active systems, meaning they consume energy in some fashion. There are primarily two types: Mechanical systems and thermal systems. Excluding manual labour, as it is not an engineered system, mechanical systems include commonplace things like windshield wipers and less common automated robots [42]. These utilize moving parts and require regular maintenance, which can make them expensive to operate over time.

Thermal systems use energy to produce or transport heat so that snow and ice may be melted. This is common on aircraft wings [43] as a safety system against icing of the wings. It is also implemented on e.g. wind power turbine blades [44] and car windows. Thermal systems are generally cheaper to maintain but can be energy intensive to operate, increasing the cost. As BIPV is a cost sensitive technology, active thermal systems have generally been avoided. A recent study, however, has shown that it may be possible, through proper planning, to attain increased annual production by implementing active heating of PV only when most beneficial [45].

2.3.2 Passive management systems

As adhesion of snow and ice, and accretion of ice occur by very different processes, the mitigation of these must be approached with specific intent. While most ice adhesion mitigation research has focused on various implementations of superhydrophobicity [46–48] and shedding inducing measures [49,50], snow adhesion research has primarily been divided between superhydrophobicity and hydrophilicity [26]. Ice accretion mitigation has almost exclusively been focused on superhydrophobicity, as the prime objective is to repel and remove water faster than it can freeze [51–54].

2.3.2.1 Superhydrophobicity

As most forms of cold precipitation is accompanied by liquid water or a LLL, the minimization of hydrogen bond formation is a vital part of their adhesion mitigation. This is most often approached by surface modifications with fluorocarbons, the use of which is likely to be prohibited in the near future. A side effect of this is superhydrophobicity, which may have additional benefits such as self-cleaning or anti-fouling properties.

Superhydrophobicity is defined as a water droplet static contact angle (CA) above 150° and a low contact angle hysteresis (CAH), shown in Figure 2.5. This is attained by (i) impeded ability of the surface to form hydrogen bonds with water molecules, and (ii) increased surface roughness [55,56]. Surface roughness lowers the interface contact area, thereby minimizing the number of bonds, and can be implemented on several scales typically on the nanometre scale and/or the micrometre scale.

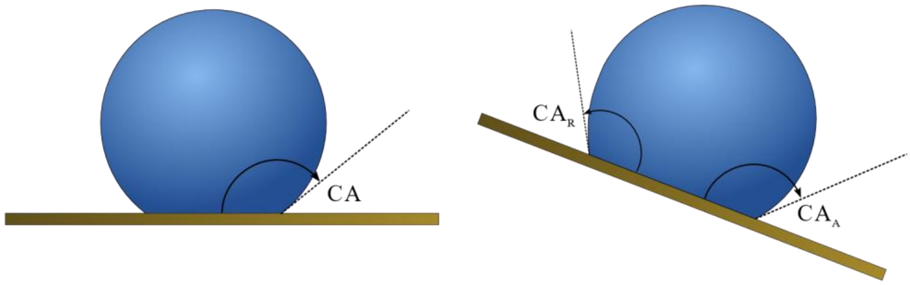

Figure 2.5: Schematic illustration of contact angle (CA) of a sessile droplet (left), and advancing (CA_A) and receding (CA_R) contact angles on a tilted plane (right). Contact angle hysteresis (CAH) is defined as the difference between CA_A and CA_R.

2.3.2.2 Ice adhesion mitigation (Icephobicity)

The adhesion of ice is typically mitigated through surface designs that implement superhydrophobicity in some manner. Some have micro-structured [56], nano-structured [57], or hierarchical structures [52]. It was, however, found by Varanasi et al. [58] that microstructured surfaces, despite superhydrophobicity, are sensitive to frost formation within the structure. This effectively renders the surface incapable of reducing ice adhesion as ice adheres very well to the frost crystals. Thereby, the structuring begins to work against the intended purpose by allowing the ice formation to penetrate the structure and catch on the protruding asperities. This problem does not, however, present on nanostructured surfaces as the asperities are often small enough to force coalescing droplets out to the surface before they can freeze, and shed the water droplets by virtue of superhydrophobicity [59].

Other than superhydrophobicity, some strategies attempt to attain a facilitated CIP by combining superhydrophobicity with soft substrates [49,50]. The flexing of the substrate under load allows for the induction of stress concentration in multiple locations which may initiate cracking [60]. There are also examples of surfaces that are smooth and hard [61,62], often focusing heavily on superhydrophobicity and/or reduction of the bonding strength overall.

2.3.2.3 Ice accretion mitigation (Frostphobicity)

While the melting point of water can be depressed through confinement, below the effective melting point, water will freeze. It may, however, not do so immediately, opening for the possibility of shedding the liquid water which is easier accomplished than with the solid ice crystals.

Ice accretion generally occurs through two processes: Desublimation or condensation of atmospheric water vapour, and the freezing of incident water droplets. In both cases, the object is to repel the water before ice crystals can form, making superhydrophobic surfaces a natural choice. By utilizing a very fine structures surface, the inherent confinement of droplets formed within the structure can ensure a depressed melting point for droplets within the structure. As they coalesce, they are forced out of the structure and, if the surface is properly designed, shed before the growing droplets have a chance to freeze. As shown by Hao et al. [59], however, frost may form even on superhydrophobic surfaces with condensation expulsion, if the surface is not perfectly clean. This illustrates the difficulty maintaining the effect over time in a natural setting where contaminants are generally numerous. It also indicates the importance of attaining a degree of self-cleaning, which commonly relies on superhydrophobicity as well.

The superhydrophobic effect may be further enhanced by combining structuring hierarchically, further reducing the number of contact points of an expelled coalescing droplet. This could aid the frostphobicity by reducing the thermal energy transfer between substrate and reducing the potential adhesion points of a frozen droplet that must be shed.

2.3.2.4 Snow adhesion mitigation (Snowphobicity)

Generally, snow adhesion research has followed the same trajectory as ice adhesion research, starting from a superhydrophobicity perspective. Kako et al. [26] established that superhydrophobicity indeed appears to reduce snow adhesion, though did so using a simulated snow made from water and very fine glass beads. While exhibiting similar mechanical properties to the wet snow it was to simulate, the lack of crystal complexity may yield somewhat expected results.

Approaching snow adhesion from superhydrophobicity appears a sound strategy but has to be coupled with the interaction between snow crystal and substrate structure. Mechanical interlocking between snow crystals and asperities on the surface may have a profound impact on the adhesion trends, especially as the LWC shifts towards dryer snow. At very low levels of LWC, it may be that the adhesion behaviour more closely resembles dry static friction.

Research materials and methods

3 Research materials and methods

The research methods and materials used in the acquisition of the results described in this thesis, will here be described briefly. The interested reader is directed to the publications (Articles I-VI) for more detailed and specific descriptions.

3.1 Literature review

Two literature reviews have been performed in this thesis project, described in Articles I and II. These were both approached as qualitative reviews of published articles through the search engines Google Scholar and Web of Science, to ascertain the state-of-the-art.

3.2 Snow synthesis

In the course of reviewing the field of snow adhesion and its effects and mitigation, it was found that the vast majority of research was either performed *in-situ*, i.e. outdoors, using natural snow [8,9,63], or using simulated snow, i.e. other materials adapted to mimic the behaviour of snow [26]. Experiments performed *in-situ* carry the inherent disadvantage of poorly controlled ambient condition, making the results difficult, or even impossible, to correlate between snow events in a detailed manner. It also makes accurate reproduction of the experiment very difficult. With simulated snow, the results can be correlated between experiments though they may not accurately represent the behaviour observed with natural snow as the conditions can vary greatly.

In order to conduct experiments in a controlled manner, relatable to the behaviour of real snow, synthetic snow has been manufactured in a laboratory environment. An apparatus is placed in a cold room, typically kept at -20°C, where air is ventilated over a warm water bath to absorb water vapor as it heats up. The air is then lead through an unheated chamber with steel wire grids hung in several layers. The cooling air condensates water on the cold wire grid forming large rime crystals similar to stellar snow crystals as can be seen in Figure 3.1. The wire grid is regularly vibrated to shed the crystals into a collection tray from which it can be taken for experimentation. The process and equipment is described in detail by Giudici et al. [64].

Figure 3.1: Synthetic snow crystals growing on steel wire. Curtesy of M. Dahl Fenre at the Norwegian University of Science and Technology (NTNU), Trondheim.

3.3 Snow adhesion analysis

Typically, the adhesion of ice is defined as the shear force per area required to attain interfacial failure between an ice sample and the substrate. While this approach has been challenged in recent years [41,60], it remains the most commonly used and is widely accepted. Therefore is has been chosen as the basis for snow adhesion as well [26].

As no widely accepted method for controlled snow adhesion testing was available, this thesis contributed by developing such a method, as described in article III. The tilted table approach is an old technology that proved to work in low snow adhesion regime situations (upper limit defined by equation 1, at 90° tilt angle). This approach utilizes gravity to apply an even force throughout a snow sample on a dynamically tilted table, from which a critical tilt angel is obtained.

The table is set up in a cold room with controlled environmental parameters and the substrate sample of interest is attached to the table. A sample of synthetic snow, as described previously, is produced, weighed, and placed on the substrate. The table is then tilted gradually until a critical tilt angle is attained where the sample breaks away from the substrate or begins to slide, as seen in Figure 3.2. This event, and the angle at which it occurs, is captured by camera and analysed later.

Several parameters may be varied in the conduction of this experiment. The temperature and relative humidity may be varied (though, as described in article III, the facilities in question had no direct regulatory control over relative humidity), the time between placement on the substrate and tilting start may be varied, and all aspects of snow sample production may be varied (size, formation, age, etc.).

The resulting tilt angle is translated to an adhesion level as

$$\sigma = \frac{mg}{A} \sin\theta \tag{6}$$

where m is the snow sample mass, g is the gravitational constant, A is the interface area, and θ is the critical tilt angle. In order to compare the adhesion of samples with a variation in density, the adhesion must then be normalized by the density of contact points at the interface. As these logically scale in the same manner as volumetric density (by percent of solid), assuming the volumetric density is approximately uniform, the results are normalized by volumetric snow sample density towards 100 kg/m^3.

$$\sigma' = \sigma \frac{100}{\rho} \tag{7}$$

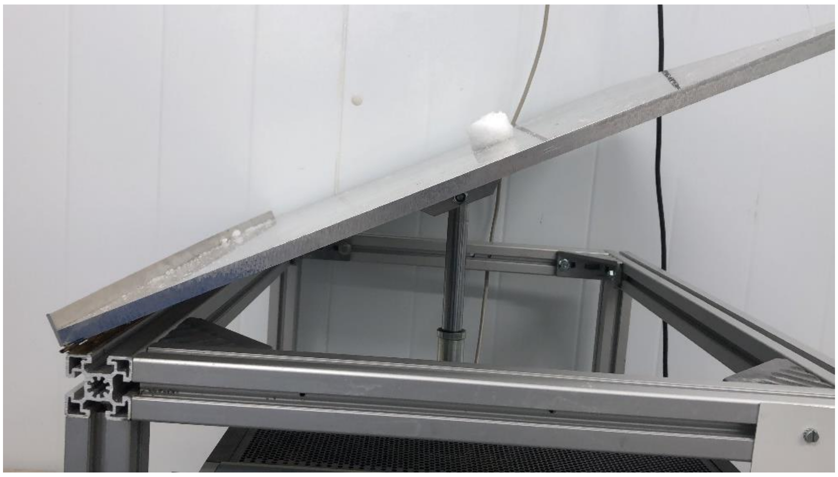

Figure 3.2: Experimental setup example. Here seen without tilt measuring equipment and camera.

3.4 Snow adhesion on icephobic surfaces

The adhesion of snow and ice has commonly been included in the term *icephobic*. This implies the assumption that adhesion of ice and snow may be mitigated in the same manner. The snow adhesion analysis method developed in this thesis, allowed the opportunity to test this assumption.

In Article IV, snow adhesion is tested using the method described previously on some known icephobic surfaces along with some reference surfaces. A slippery lubricant impregnated porous surface (SLIPS) and commercial low adhesion coating called EC-3100™ from Ecological Coatings LLC were employed as the icephobic surfaces, due to their documented low ice adhesin [65,66]. These were compared to a unidirectionally brushed Al6061-T6 aluminium substrate, identical to the one used as a reference to the EC-3100™ [65], and a plain float glass substrate.

Synthetic snow, produced at -20°C as described previously, was used at -10°C and at -18°C within 12 h of production. For more detailed information, please refer to Article IV in Appendix A.

3.5 Snow adhesion on smooth and rough surfaces

In order to compare the influence of surface roughness, four float glass samples were prepared with increasing levels of unidirectional polishing with water suspended boron carbide particles: (i) plain/smooth glass, (ii) polished with 80 grit carbide suspension, (iii) polished with 180 grit carbide suspension, and (iii) polished with 320 grit carbide suspension.

By means of the method presented in Article III, synthetic snow, produced at -20°C as previously described, was applied in cylindric samples (height: 25 mm, diameter: 45 mm) to the four surfaces. Snow adhesion was analysed at -10°C within 12 h of snow production

Roughness analysis was required to characterize the attained roughness levels of glass samples used in article V. This was performed by both infinite focus microscopy (IFM) and atomic force microscopy (AFM) in collaboration with SINTEF Industry.

3.6 Cold room laboratory

The ambient conditions of the laboratory cold room used in the analysis of snow adhesion is an important factor in the repeatability of results. The available facilities at NTNU allows for accurate control of temperature wile passively monitoring relative humidity. The temperature and RH can be seen recorded over nearly 12 h in Figure 3.3. Standard deviation of temperature was established at ±0.5°C, and of humidity at ±6 p.p.

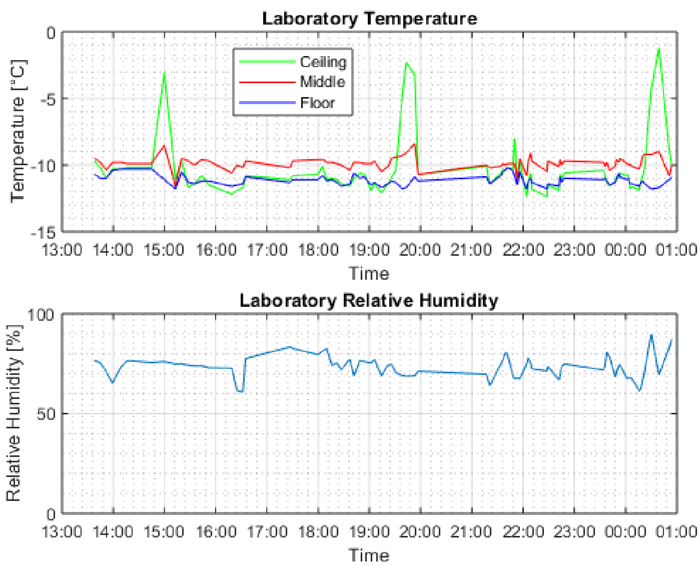

Figure 3.3: Temperature and humidity in cold room laboratory. "Middle" implies approximately half way between floor and ceiling.

Accurate temperature control is a vital aspect to be able to control for experiments like the ones presented here. While the temperature regularly spikes at the ceiling level due to de-frosting cycles, the temperature remains stable at both floor and mid-height.

Humidity can carry significant implications to adhesion of condensation occurs and ice/frost begins to accrete. As no condensation or frost/ice accretion has been observed in the course of the experiments, it can be assumed that the effects are minor at most. Given the recorded stability, the humidity can also be assumed relatively constant.

Summary of experimental findings

4 Summary of experimental findings

The main findings from the experimental studies are here summarized and placed in continuous context. For specific details and more explicit presentations, please see Articles III-V.

4.1 Snow adhesion analysis method

4.1.1 Abilities

The method developed for snow adhesion testing, presented in Article III, was demonstrated to be able to differentiate some common engineering materials. Five substrates (listed below) were tested. Three common engineering materials and two modified examples of these three.

- Monocrystalline <100> Silicon
- Monocrystalline <100> Silicon, etched by potassium hydroxide (KOH)
- Nominally smooth aluminium Al5774
- Plain float glass
- Plain float glass coated with commercially available hydrophobicity spray

All three plain engineering materials exhibited adhesion levels significantly different from one another, as seen in Figure 4.1. The structured silicon, however, exhibited adhesion levels beyond the limitations of the methods capacity, whereas the coated glass exhibited adhesion too similar to the uncoated glass to establish a statistically significant difference.

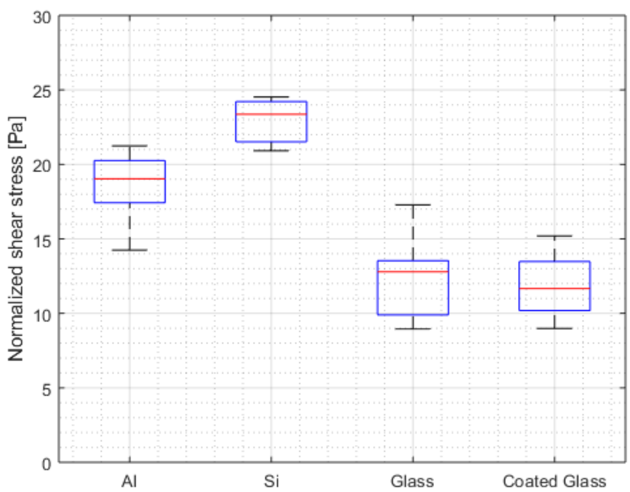

Figure 4.1: Measured critical shear stress on different materials, normalized for snow density. Etched silicon results excluded due to adhesion results exceeding the limitations of measurement.

4.1.2 Limitations

The method has an obvious limit of applicable force and can therefore not evaluate adhesions above 25 Pa for the sample size employed, as seen in the evaluation of roughened glass surfaces

(Figure 4.5). For low adhesion materials however, this has been seen sufficient and it is for such surfaces the method was developed.

In addition to general method limitations, two potentially influencing factors were also analysed: The influence of the snow sample geometry, and the snow sample time spent on substrate (resting time). Whereas the geometry of the snow sample was not seen to have a significant effect, the resting time was seen to have an apparent effect in the first few minutes. This is consistent with developing interfacial molecular bonds.

4.2 Snow adhesion and ice adhesion

Ice adhesion results from testing the SLIPS and EC-3100™ shows that both coating materials do indeed lower ice adhesion, compared to other engineering materials, as seen in Figure 4.2 [65,66]. Testing these materials for snow adhesion, however, has presented an entirely different trend, seen in Figure 4.3.

Snow adhesion to brushed aluminium, SLIPS, and EC-3100™ was compared to plain (smooth) float glass for common reference as it is the primary cover material in photovoltaics. The experiments showed a marginal reduction of adhesion by the EC-3100™ material while the SLIPS material showed an increase in snow adhesion, similar to the results from the brushed aluminium material. Another interesting feature of this study is that ice adhesion appears relatively unaffected by a temperature shift from -10°C to -18°C [65], whereas snow adhesion showed a clear and consistent increase in the same range.

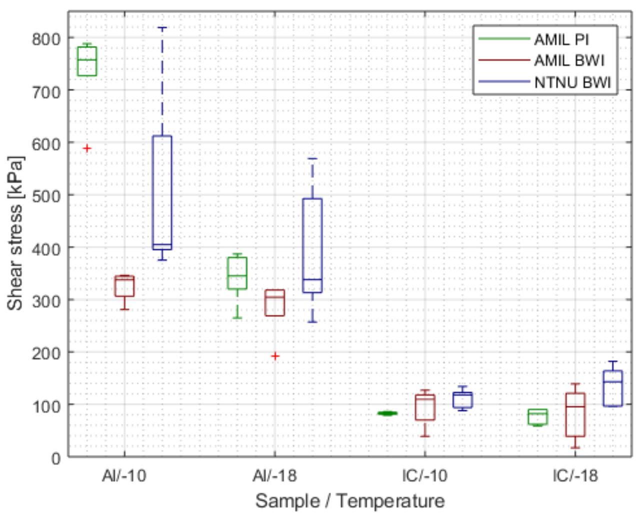

Figure 4.2: Ice adhesion results reproduced from Rønneberg et al. [65].

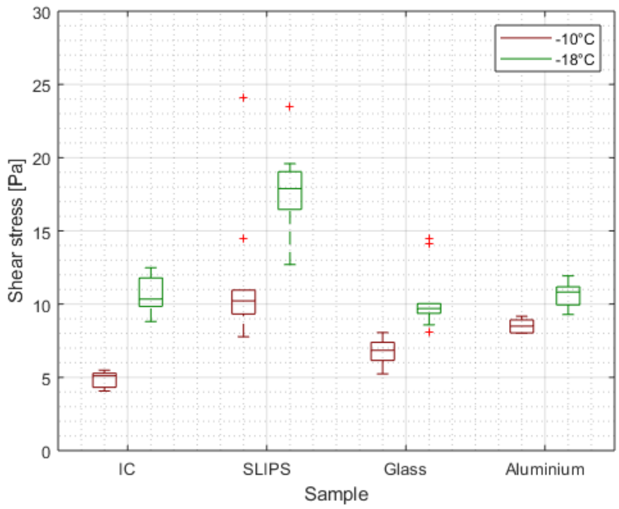

Figure 4.3: Snow adhesion results. Red +-signs indicate outliers as defined by values exceeding 1.5 standard deviations from the median.

4.2.1 Hypothesized cause of difference

While ice adhesion and snow adhesion both should be affected by superhydrophobic surfaces that minimize the ability to form hydrogen bonds, the materials investigated here were not superhydrophobic.

The dislodging of bulk water ice (BWI) from a substrate, normally occurs as crack initiation and propagation (CIP) throughout the interface. This has been an adhesion reduction approach in several studies [49,50,60,67] and is a well-known process.

CIP between solid ice and a mechanically soft substrate, such as the SLIPS, may have played a major role in the successful mitigation of adhesion to such an extent. Such processes have been investigated previously by Beemer et al. [68] and Irajizad et al. [60]. Snow adhesion was found to not be significantly different between the soft SLIPS and the harder EC-3100™. The CIP effect thus appears to have a minimal influence on snow adhesion.

There have been no apparent suggestions for release mechanisms of adhering snow as of yet. It was speculated in Article IV, however, that the lack of strong bonding between snow crystals, may allow for some ductility of the snowpack close to the interfacial, allowing the snow to absorb energy as it deforms. On an unyielding substrate, any energy absorption will take place in the snow. A similar argument was made by Cai et al. [40], though not applied specifically to porous materials such as snow.

This could then allow for locally dislodging regions as the snow deforms (Figure 4.4, A-C), leading to load concentration and facilitate the interfacial failure. On a yielding substrate, however, the substrate may also deform and absorb energy (Figure 4.4, D-F). This could allow the interfacial regions that would otherwise dislodge, to remain bonded to the substrate longer (to higher applied forces). This would be congruent with the larger adhesion to the softer SLIPS substrate material. This process schematically shown in Figure 4.4 for a ridged and a soft substrate. If this hypothesis is correct, the implication would be that a mechanically hard substrate would be preferable in the case of snow adhesion mitigation.

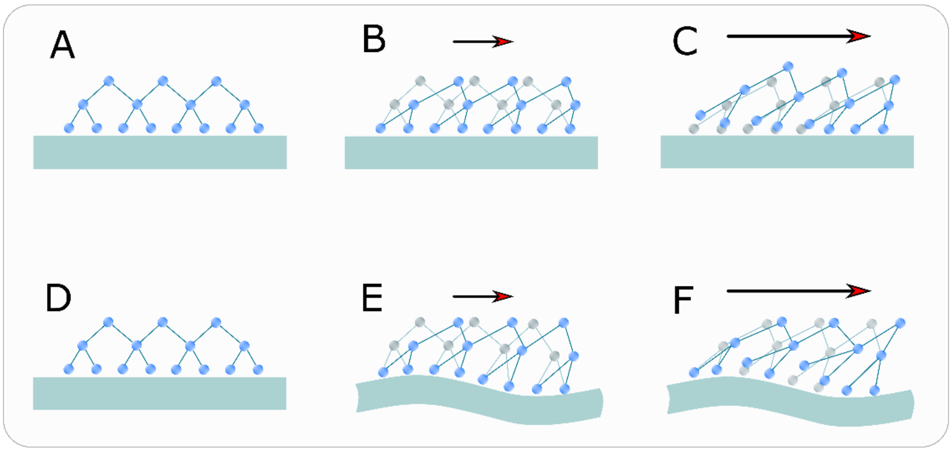

Figure 4.4: Schematic illustration of hypothetical release mechanisms for snow. A-C depicts snow on a hard surface under (A) no load, (B) moderate load, and (C) larger load. D-F depicts the snow on a soft substrate under (D) no load, (E) moderate load, and (F) larger load.

4.3 Snow adhesion and roughness

In Article V, it was investigated how surface roughness of float glass impacts snow adhesion. As can be seen in Figure 4.5, snow adhesion increased significantly with any increase in level of roughness from the smooth glass. A hitherto unexplained dip occurred at the mid-level of roughness (180-grit), though it appears likely that the effect is not an aberration as it occurs in both directions of brushing. Comparing the parallel and perpendicular roughnesses, indicates that the polishing appears to have produced somewhat isotropic properties, which is congruent with the adhesion results.

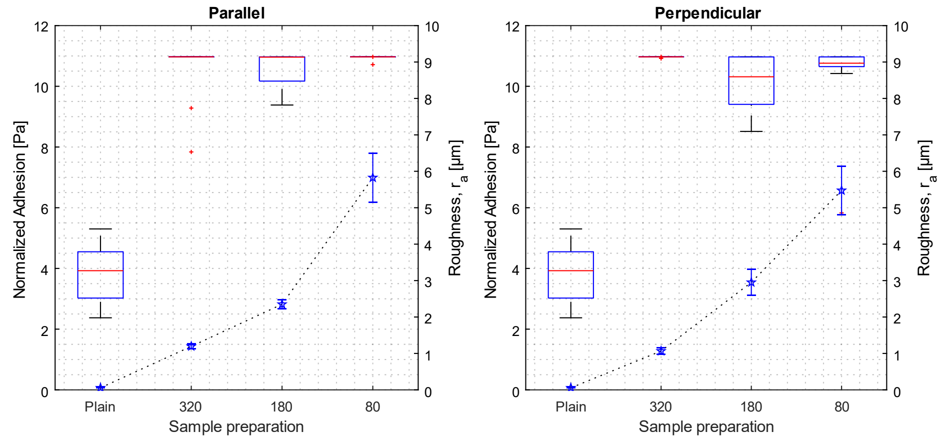

Figure 4.5: Normalized adhesion measured on float glass samples of varying roughness. Adhesion is indicated by box-plots and roughness by blue stars with standard deviation bars. Red +-signs indicate outliers as defied by values exceeding 1.5 standard deviations from the median.

The limits of the adhesion measuring method were surpassed repeatedly and the results indicate that roughened glass is near or beyond its limit. The point of the study, however, was not to quantify in detail the impact of roughness on snow adhesion, but rather to explore the limits of the method and verify that increased roughness would increase adhesion. It was not expected that the finest grit polishing (320-grit) would display such high adhesion, though it shows just how immediate the effect of roughness can be on snow adhesion.

Summary of theoretical developments

5 Summary of theoretical developments

Based on the state-of-the-art analysis in Articles I and II, the research focus of this thesis was narrowed from surface design for ice and snow mitigation on BIPV, to focus specifically on snow adhesion mitigation. This development stems from an evolution of the theoretical understanding of the field, leading to suggested developments of the terminology as well as a scheme for classification proposed in Article VI.

5.1 Icephobicity and its interpretation

Icephobicity is commonly defined by (i) the mitigation of ice adhesion [25,67], (ii) the resistance to frost accretion [25,58], (iii) the prolonged freezing of water droplets [25,69], or (iv) the mitigation of snow adhesion [25]. These four aspects stem from fundamentally different thermodynamic processes, making it difficult to pinpoint what icephobicity implies.

Results from Article IV suggests that icephobic surfaces cannot be implicitly assumed to mitigate snow adhesion. Other studies [70] indicate that resistance to frost accretion and freezing suppression of droplets necessitates structured surfaces, which Article V indicates would be detrimental to snow adhesion mitigation.

In order to better communicate and understanding the effects of an engineered surfaces requirements and/or abilities, the terminology should be separated by thermodynamic processes. In Article VI, a separation of terms has been suggested where ice adhesion mitigation retains the term *icephobic*, snow adhesion mitigation is termed *snowphobic*, and ice accretion is termed *frostphobic*. An umbrella term is also introduced to describe the mitigation of cold precipitation in general, dubbed *crynerophobic* (Greek: Cryo = cold, Nero = water, Phobos = fear), seen graphically represented in Figure 5.1.

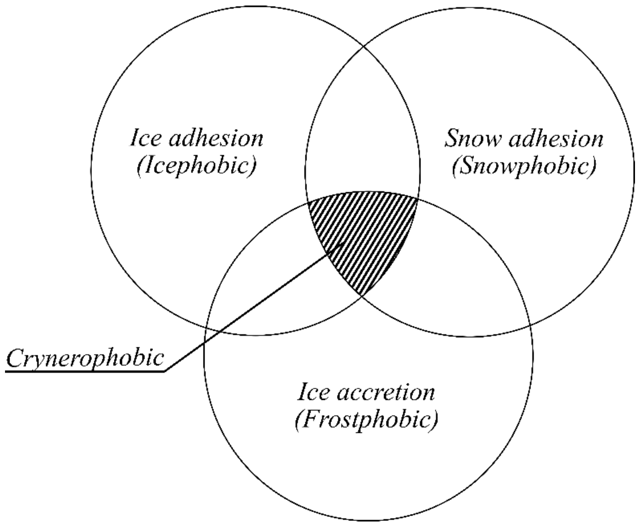

Figure 5.1: Graphic representation of the separation of terminology.

As Figure 5.1 suggests, there may be significant overlap by two or more of the aspects. E.g. superhydrophobicity appears beneficial to some degree to most forms of cold precipitation [25], while vital for others [54]. Naturally, the specific engineering case must ultimately decide how much overlap, if any, is required for the intended application.

5.2 Classification development

The ability to easily communicate certifiable performance of a crynerophobic surface design is of vital importance for the applicability of a product in a commercial setting. To this end, a scheme for classification of crynerophobic performance level has been suggested in Article VI.

The syntax, developed to emulate the ingress protection code (IP) classification [71], is defined as shown in Figure 5.2. It specifies the level of adhesion for ice, the level of adhesion for snow, and the ice accretion delay time as levels from 1-9. This also calls for ice type, snow type, and pathway of accretion to be defined for each classification. Thus, a product may be classified in a manner specific to its application, or by multiple if required.

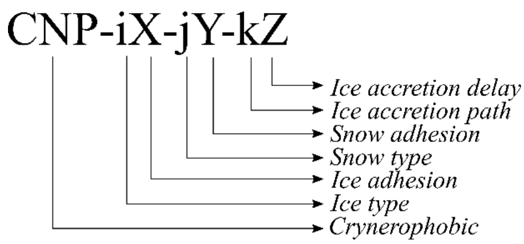

Figure 5.2: Syntax suggested for classification of crynerphobic aspects.

The suggested scheme defines four ice types and four snow types, shown in Figure 5.3, that greatly differ in mechanical and/or adhesive properties. The ice types are *glace ice*, *hard rime*, and *soft rime*, as defined in the ISO standard, ISO 2494:2017. BWI is added to this, as its properties have been suggested to differ from glaze ice. The snow types include *wet snow* and *dry snow*, as well as *hail* and *graupel*. These are all regarded as snow types due to their formation prior to surface contact, whereas the ice types form directly on the surface.

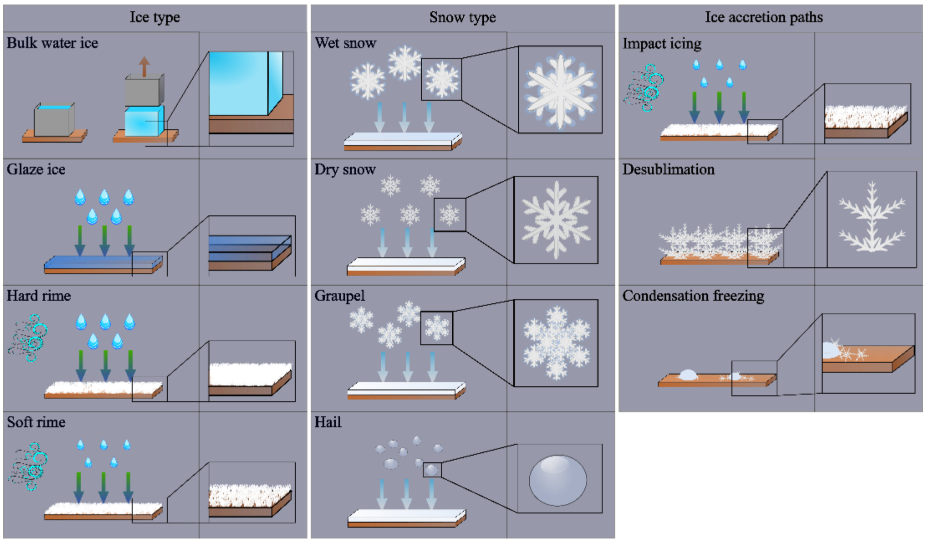

Figure 5.3: Genesis of snow and ice on generalized surfaces: Snow and ice types illustrated and exaggerated for intuitive understanding of unique features. Each type shows both process of formation and a detailed excerpt, where it should be noted that the formation of hard and soft rime occurs through a process of freezing rain/drizzle, often in strong wind.

Future perspective

6 Future perspective

6.1 Snow adhesion on BIPV

In some regions snow can dramatically impact the annual production of any PV installation and, given the present cost sensitivity of BIPV, may be the deciding factor between investing or not. It is therefore imperative that methods are developed to combat the problem if BIPV is to be widely implemented also in cold regions.

Given the evidence gleaned from the research presented here and elsewhere, some basic guidelines can be constructed for successful snow adhesion mitigation:

1. A hard surface may reduce the deformation energy required to initiate sliding of snow on a surface (Article IV).
2. A superhydrophobic surface should allow for reduced ability of the snow to form hydrogen bonds with the surface (Unpublished results).
3. A smooth surface should mitigate the mechanical adhesion between surface and the natural roughness of snow (Article V).

6.2 Measuring snow adhesion

The measuring methodology developed and used here, is a simple approach designed for measuring snow adhesion on possible snowphobic surfaces. A primary design parameter was to use the least complex setup possible, without compromising accuracy too much. For universities and other academic entities, advanced measuring equipment is a significant investment, though it is commonly done as their mandate is to push the envelope and expand the horizon of knowledge. For such goals, more complex designs may be required, e.g. to establish a generalized model for adhesion on rough surfaces. Here, the tilted-table approach has been shown not to have sufficient range.

Developers of surface coating technologies, such as could be employed for snow adhesion mitigation, are often unable or unwilling to invest in expensive measuring equipment for tasks as specific as snow and/or ice adhesion. Thus, there is a significant advantage to the implementation of simple solutions. Even more advantageous would be methods of measurement that can be repurposed for other tasks when needed, such as a tilted table might.

6.3 Implications of success

Successful mitigation of snow adhesion on BIPV will have several implications of which some are well-known while others are more seldomly discussed. Here more of them will be very briefly presented so as to attain a more balanced view.

6.3.1 Financial benefit

The most well-discussed outcome of successful mitigation is the financial aspect. It would grant a more competitive lifetime cost of BIPV when compared to traditional alternatives. This, however, is not likely to be a dramatic impact, considering the production losses commonly range from 1-10% annually.

6.3.2 Legislation

Traditionally, snow catchers are mandatory by law in order to keep snow from falling on people and property. This is in direct opposition to the passive and continuous snow removal as passive removal hinges on a free path for snow to move with little or no hindrance. If a successful snowphobic surface is attained, the legislation may have to be amended for implementation to be meaningful.

6.3.3 Design of BIPV

An apparently less discussed topic is the implications to BIPV design. In order for snow to slid from element to element in a BIPV installation, frames, and other protruding elements such as fastening screws, have to be removed. These would otherwise likely render any surface coating effectively useless.

6.4 Future research

Snow adhesion is significantly less explored than ice adhesion and thus there are several matters that are better understood in ice adhesion. These should be examined specifically for snow.

1. The role and existence of the LLL.

   The existence of a LLL on ice has been researched extensively for ice and is deemed likely to be present in snow as well. Confirmation of this and what the consequences of its existence might be, are hitherto unknown.

2. The impact of snow type.

   Ice types have been explored and tested in various ways, though the impact of their differences has not always been recognized. Similarly, snow types as defined by crystal size, liquid water content, age, etc. should be explored and correlated.

There are also aspects that either do not have a corollary in ice adhesion research, or that have yet to be fully understood also there:

1. Liquid water content of snow dependence on temperature.

   It has been recognized that LWC has a transition region between -1°C and -2°C. Below -2°C, snow is often regarded as dry whereas above -1°C it is generally regarded as wet. This should be more accurately defined and underpinned by modelling to explain the behaviour.

2. Relation between adhesion of snow of different wetness and hydrophobicity.

   Once a better understanding of the wetness of snow has been attained, it should be related to hydrophobicity, as it is the most common approach to ice adhesion and often assumed to translate to snow. This cannot be assumed true for all levels of LWC and must be verified.

3. The interplay between traditional dry friction and snow adhesion, and how they relate to capillary adhesive forces.

   Traditional dry friction is a field of research that often overlaps with adhesion research. How static friction related to adhesion and what forces one should use to model the behaviour, is not always agreed upon. Illuminating this area could significantly benefit the understanding of snow adhesion and how it may be mitigated.

Concluding remarks

7 Concluding remarks

As each facet of cold precipitation has a different fundamental nature, their impact mitigation should also be approached in different ways, though they may overlap at times. Snow, being the cold precipitation most relevant for BIPV optimization in cold climates, was chosen as the focus of this thesis.

The field of snow adhesion has barely been scratched at the surface. The articles in this thesis represent some of the first steps towards exploration of a field that is relatively unexplored and appears poorly understood. They endeavour to communicate the importance of the separation of the cold precipitation facets, and also suggested a means of communicating levels of success between professionals through a classification scheme in Article IV.

Articles III-V have treated snow adhesion experimentation and methodological developments. One of the cornerstones of the scientific principle is that of reproducibility and there are two rules of thumb that may be seen as fundamental requirements for the general acceptance of results:

1. Results that are not yet independently reproduced cannot be regarded as objective truths or established facts.
2. Results obtained in a manner that cannot be reproduced, cannot be regarded as adhering to the scientific principle.

While the second rule appears harsh and arguments are often made for exceptions, it remains a fundamental tenant of the scientific principle. Results may still be interesting, but care should then be taken to recognize the potential unreliability of them when inferring new ideas of how nature behaves. In order to properly perform experiments that may be repeated and corroborated by independent research teams, a controlled method for snow adhesion measurement was developed in Article III. Synthetic snow was also produced for these experiments, in a repeatable manner with tuneable properties that very closely resemble genuine snow.

The results obtained indicate that soft coatings yield higher snow adhesion as does any surface roughness. While beneficial for attaining superhydrophobicity, structured surfaces may not be a suitable choice for reducing snow adhesion. Rather, coatings should be designed superhydrophobic, smooth, and hard.

References

[1] M.P. Brennan, A.L. Abramase, R.W. Andrews, J.M. Pearce, Effects of spectral albedo on solar photovoltaic devices, Sol. Energy Mater. Sol. Cells. 124 (2014) 111–116. doi:10.1016/j.solmat.2014.01.046.

[2] R.W. Andrews, J.M. Pearce, The effect of spectral albedo on amorphous silicon and crystalline silicon solar photovoltaic device performance, Sol. Energy. 91 (2013) 233–241. doi:10.1016/j.solener.2013.01.030.

[3] E. Molin, B. Stridh, A. Molin, E. Wackelgard, Experimental yield study of bifacial PV modules in nordic conditions, IEEE J. Photovoltaics. 8 (2018) 1457–1463. doi:10.1109/JPHOTOV.2018.2865168.

[4] H. Islam, M. Jollands, S. Setunge, N. Haque, M.A. Bhuiyan, Life cycle assessment and life cycle cost implications for roofing and floor designs in residential buildings, Energy Build. 104 (2015) 250–263. doi:10.1016/j.enbuild.2015.07.017.

[5] A. de Gracia, L. Navarro, A. Castell, D. Boer, L.F. Cabeza, Life cycle assessment of a ventilated facade with PCM in its air chamber, Sol. Energy. 104 (2014) 115–123. doi:10.1016/j.solener.2013.07.023.

[6] T. Georgitsioti, N. Pearsall, I. Forbes, G. Pillai, A combined model for PV system lifetime energy prediction and annual energy assessment, Sol. Energy. 183 (2019) 738–744. doi:10.1016/j.solener.2019.03.055.

[7] R.E. Pawluk, Y. Chen, Y. She, Photovoltaic electricity generation loss due to snow – A literature review on influence factors, estimation, and mitigation, Renew. Sustain. Energy Rev. 107 (2019) 171–182. doi:10.1016/j.rser.2018.12.031.

[8] R.W. Andrews, A. Pollard, J.M. Pearce, The effects of snowfall on solar photovoltaic performance, Sol. Energy. 92 (2013) 84–97. doi:10.1016/j.solener.2013.02.014.

[9] B. Marion, R. Schaefer, H. Caine, G. Sanchez, Measured and modeled photovoltaic system energy losses from snow for Colorado and Wisconsin locations, Sol. Energy. 97 (2013) 112–121. doi:10.1016/j.solener.2013.07.029.

[10] A. Rahmatmand, S.J. Harrison, P.H. Oosthuizen, Evaluation of removing snow and ice from photovoltaic-thermal (PV/T) panels by circulating hot water, Sol. Energy. 179 (2019) 226–235. doi:10.1016/j.solener.2018.12.053.

[11] C.N. Nanev, Theory of Nucleation, in: Handb. Cryst. Growth Second Ed., Elsevier Inc., 2015: pp. 315–358. doi:10.1016/B978-0-444-56369-9.00007-1.

[12] R. DeHoff, Thermodynamics in Materials Science, CRC Press, 2006. doi:10.15713/ins.mmj.3.

[13] N.H. Fletcher, Size effect in heterogeneous nucleation, J. Chem. Phys. 29 (1958) 572–576. doi:10.1063/1.1744540.

[14] N.H. Fletcher, Nucleation by crystalline particles, J. Chem. Phys. 38 (1963) 237–240. doi:10.1063/1.1733468.

[15] O. Petrov, I. Furó, Curvature-dependent metastability of the solid phase and the freezing-melting hysteresis in pores, Phys. Rev. E - Stat. Nonlinear, Soft Matter Phys. 73 (2006). doi:10.1103/PhysRevE.73.011608.

[16] E. Tombari, G. Salvetti, C. Ferrari, G.P. Johari, Thermodynamic functions of water and ice confined to 2 nm radius pores, J. Chem. Phys. 122 (2005) 104712. doi:10.1063/1.1862244.

[17] A. Baranyai, A. Bartók, A.A. Chialvo, Computer simulation of the 13 crystalline phases of ice, J. Chem. Phys. 123 (2005) 926. doi:10.1063/1.1989313.

[18] J. Major, D.M. Gray, D.H. Male, Handbook of Snow: Principles, Processes, Management and Use, The Blackburn Press, New Jersey, 1983. doi:10.2307/1550934.

[19] K.G. Libbrecht, The physics of snow crystals, Reports Prog. Phys. 68 (2005) 855–895. doi:10.1088/0034-4885/68/4/R03.

[20] C. Magono, Meteorological Classification of Snow Crystals, J. Japanese Soc. Snow Ice. 24 (1962) 33–37. doi:10.5331/seppyo.24.33.

[21] T. Nishinaga, Handbook of Crystal Growth, 2nd ed., Elsevier Science Ltd, 2014. doi:10.1016/b978-0-444-88908-9.50001-2.

[22] C. Fierz, R.L. Armstrong, Y. Durand, P. Etchevers, E. Greene, D.M. McClung, K. Nishimura, P.K. Satyawali, S. a. Sokratov, The international classification for seasonal snow on the ground, Paris, 2009.

[23] W.W. Mullins, R.F. Sekerka, Morphological Stability of a Particle Growing by Diffusion or Heat Flow, J. Appl. Phys. 34 (1963) 323–329. doi:10.1063/1.1702607.

[24] K.G. Libbrecht, Physical Dynamics of Ice Crystal Growth, (2017). doi:10.1146/annurev-matsci-070616.

[25] H. Sojoudi, M. Wang, N.D. Boscher, G.H. McKinley, K.K. Gleason, Durable and scalable icephobic surfaces: similarities and distinctions from superhydrophobic surfaces, Soft Matter. 12 (2016) 1938–1963. doi:10.1039/C5SM02295A.

[26] T. Kako, A. Nakajima, H. Irie, Z. Kato, K. Uematsu, T. Watanabe, K. Hashimoto, Adhesion and sliding of wet snow on a super-hydrophobic surface with hydrophilic channels, J. Mater. Sci. 39 (2004) 547–555. doi:10.1023/B:JMSC.0000011510.92644.3f.

[27] T.E.W. Schuma, The theory of hailstone formation, Q. J. R. Meteorol. Soc. 64 (1938) 3–21. doi:10.1002/qj.49706427303.

[28] R.F. Reinking, Formation of Graupel, J. Appl. Meteorol. 14 (1975) 745–754. doi:10.1175/1520-0450(1975)014<0745:fog>2.0.co;2.

[29] S.C. Colbeck, Sintering in a dry snow cover, J. Appl. Phys. 84 (1998) 4585–4589. doi:10.1063/1.368684.

[30] J.R. Blackford, Sintering and microstructure of ice: A review, J. Phys. D. Appl. Phys. 40 (2007) 355–385. doi:10.1088/0022-3727/40/21/R02.

[31] D. Kuroiwa, A Study of Ice Sintering, Tellus. 13 (1961) 252–259. doi:10.3402/tellusa.v13i2.9450.

[32] R.O. Ramseier, C.M. Keeler, The Sintering Process in Snow, 1966. doi:10.3189/s0022143000019535.

[33] D.G.R. William D. Callister, Fundamentals of Materials Science and Engineering: An Integrated Approach pp180, 4th ed., Wiley, 2009.

[34] R.M. German, Powder metallurgy and particulate materials processing : the processes, materials, products, properties and applications, 1st ed., Metal Powder Industries Federation, Princeton, New Jersey, 2005. doi:10.2353/ajpath.2008.070161.

[35] S.-J.L. Kang, Sintering: densification, grain growth, and microstructure, Elsevier, 2005. http://www.amazon.com/dp/0750663855.

[36] N. Maeno, T. Ebinuma, Pressure sintering of ice and its implication to the densification of snow at polar glaciers and ice sheets, 1983. doi:10.1021/j100244a023.

[37] S.C. Colbeck, An overview of seasonal snow metamorphism, Rev. Geophys. 20 (1982) 45–61. doi:10.1029/RG020i001p00045.

[38] W.T. Pfeffer, R. Mrugala, Temperature gradient and initial snow density as controlling factors in the formation and structure of hard depth hoar, 2002. doi:10.3189/172756502781831098.

[39] M. Sturm, C.S. Benson, Vapor transport, grain growth and depth-hoar development in the subarctic snow, 1997.

[40] X.J. Cai, J.Q. Xu, Interfacial fracture criteria based on the nominal deformation energy of interface, Theor. Appl. Fract. Mech. 75 (2015) 16–21. doi:10.1016/j.tafmec.2014.10.008.

[41] K. Golovin, A. Dhyani, M.D. Thouless, A. Tuteja, Low-interfacial toughness materials for effective large-scale deicing, Science (80-.). 364 (2019) 371–375. doi:10.1126/science.aav1266.

[42] A. Gheitasi, A. Almaliky, N. Albaqawi, Development of an automatic cleaning system for photovoltaic plants, in: Asia-Pacific Power Energy Eng. Conf. APPEEC, IEEE, 2016: pp. 1–4. doi:10.1109/APPEEC.2015.7380938.

[43] Y. Zhao, S. Chang, B. Yang, W. Zhang, M. Leng, Experimental study on the thermal performance of loop heat pipe for the aircraft anti-icing system, Int. J. Heat Mass Transf. 111 (2017) 795–803. doi:10.1016/j.ijheatmasstransfer.2017.04.009.

[44] O. Parent, A. Ilinca, Anti-icing and de-icing techniques for wind turbines: Critical review, Cold Reg. Sci. Technol. 65 (2011) 88–96. doi:10.1016/j.coldregions.2010.01.005.

[45] B.B. Aarseth, M.B. Øgaard, J. Zhu, T. Strömberg, J.A. Tsanakas, J.H. Selj, E.S. Marstein, Mitigating snow on rooftop PV systems for higher energy yield and safer roofs, 2018. doi:10.4229/35thEUPVSEC2018-6CO.3.5.

[46] N. Cohen, A. Dotan, H. Dodiuk, S. Kenig, Thermomechanical Mechanisms of Reducing Ice Adhesion on Superhydrophobic Surfaces, Langmuir. 32 (2016) 9664–9675. doi:10.1021/acs.langmuir.6b02495.

[47] S.A. Kulinich, M. Farzaneh, How Wetting Hysteresis Influences Ice Adhesion Strength on Superhydrophobic Surfaces, J. Adhes. Sci. Technol. 25 (2009) 4056–4060. doi:10.1021/la901439c.

[48] C. Antonini, M. Innocenti, T. Horn, M. Marengo, A. Amirfazli, Understanding the effect of superhydrophobic coatings on energy reduction in anti-icing systems, Cold Reg. Sci. Technol. 67 (2011) 58–67. doi:10.1016/j.coldregions.2011.02.006.

[49] Z. He, S. Xiao, H. Gao, J. He, Z. Zhang, Multiscale crack initiator promoted super-low ice adhesion surfaces, Soft Matter. 13 (2017) 6562–6568. doi:10.1039/c7sm01511a.

[50] Z. He, Y. Zhuo, J. He, Z. Zhang, Design and preparation of sandwich-like polydimethylsiloxane (PDMS) sponges with super-low ice adhesion, Soft Matter. 14 (2018) 4846–4851. doi:10.1039/c8sm00820e.

[51] Y. He, C. Jiang, P. Hu, R. Yang, W. Tian, W. Yuan, Reducing ice accumulation and adhesion by using a flexible micro-rod film, Cold Reg. Sci. Technol. 118 (2015) 57–63. doi:10.1016/j.coldregions.2015.06.001.

[52] P. Guo, Y. Zheng, M. Wen, C. Song, Y. Lin, L. Jiang, Icephobic/anti-icing properties of micro/nanostructured surfaces, Adv. Mater. 24 (2012) 2642–2648. doi:10.1002/adma.201104412.

[53] X. Sun, V.G. Damle, A. Uppal, R. Linder, S. Chandrashekar, A.R. Mohan, K. Rykaczewski, Inhibition of Condensation Frosting by Arrays of Hygroscopic Antifreeze Drops, Langmuir. 31 (2015) 13743–13752. doi:10.1021/acs.langmuir.5b03869.

[54] T.M. Schutzius, S. Jung, T. Maitra, G. Graeber, M. Köhme, D. Poulikakos, Spontaneous droplet trampolining on rigid superhydrophobic surfaces, Nature. 527 (2015) 82–85. doi:10.1038/nature15738.

[55] T.M. Schutzius, S. Jung, T. Maitra, P. Eberle, C. Antonini, C. Stamatopoulos, D. Poulikakos, Physics of icing and rational design of surfaces with extraordinary icephobicity, Langmuir. 31 (2015) 4807–4821. doi:10.1021/la502586a.

[56] S. Dash, M.T. Alt, S. V. Garimella, Hybrid surface design for robust superhydrophobicity, Langmuir. 28 (2012) 9606–9615. doi:10.1021/la301743p.

[57] P. Eberle, M.K. Tiwari, T. Maitra, D. Poulikakos, Rational nanostructuring of surfaces for extraordinary icephobicity, Nanoscale. 6 (2014) 4874–4881. doi:10.1039/c3nr06644d.

[58] K.K. Varanasi, T. Deng, J.D. Smith, M. Hsu, N. Bhate, Frost formation and ice adhesion on superhydrophobic surfaces, Appl. Phys. Lett. 97 (2010) 234102. doi:10.1063/1.3524513.

[59] Q. Hao, Y. Pang, Y. Zhao, J. Zhang, J. Feng, S. Yao, Mechanism of delayed frost growth on superhydrophobic surfaces with jumping condensates: More than interdrop freezing, Langmuir. 30 (2014) 15416–15422. doi:10.1021/la504166x.

[60] P. Irajizad, A. Al-Bayati, B. Eslami, T. Shafquat, M. Nazari, P. Jafari, V. Kashyap, A. Masoudi, D. Araya, H.

Ghasemi, Stress-localized durable icephobic surfaces, Mater. Horizons. 6 (2019) 758–766. doi:10.1039/c8mh01291a.
[61] H. Sojoudi, G.H. McKinley, K.K. Gleason, Linker-free grafting of fluorinated polymeric cross-linked network bilayers for durable reduction of ice adhesion, Mater. Horizons. 2 (2015) 91–99. doi:10.1039/c4mh00162a.
[62] M.J. Kreder, J. Alvarenga, P. Kim, J. Aizenberg, Design of anti-icing surfaces: Smooth, textured or slippery?, Nat. Rev. Mater. 1 (2016) 15003. doi:10.1038/natrevmats.2015.3.
[63] N. Heidari, J. Gwamuri, T. Townsend, J.M. Pearce, Impact of Snow and Ground Interference on Photovoltaic Electric System Performance, IEEE J. Photovoltaics. 5 (2015) 1680–1685. doi:10.1109/JPHOTOV.2015.2466448.
[64] H. Giudici, M. Dahl Fenre, A. Klein-Paste, K.-P. Rekilä, A technical description of LARS and Lumi: Two apparatus for studying tire-pavement interactions, Routes/Roads Mag. (2017) 49–54.
[65] S. Rønneberg, Y. Zhuo, C. Laforte, J. He, Z. Zhang, Interlaboratory Study of Ice Adhesion Using Different Techniques, Coatings. 9 (2019) 678. doi:10.3390/coatings9100678.
[66] T. Li, Y. Zhuo, V. Håkonsen, S. Rønneberg, J. He, Z. Zhang, Epidermal Gland Inspired Self-Repairing Slippery Lubricant-Infused Porous Coatings with Durable Low Ice Adhesion, Coatings. 9 (2019) 602. doi:10.3390/coatings9100602.
[67] V. Hejazi, K. Sobolev, M. Nosonovsky, From superhydrophobicity to icephobicity: Forces and interaction analysis, Sci. Rep. 3 (2013). doi:10.1038/srep02194.
[68] D.L. Beemer, W. Wang, A.K. Kota, Durable gels with ultra-low adhesion to ice, J. Mater. Chem. A. 4 (2016) 18253–18258. doi:10.1039/c6ta07262c.
[69] G. Graeber, T.M. Schutzius, H. Eghlidi, D. Poulikakos, Spontaneous self-dislodging of freezing water droplets and the role of wettability, Proc. Natl. Acad. Sci. 114 (2017) 11040–11045. doi:10.1073/pnas.1705952114.
[70] J.B. Boreyko, R.R. Hansen, K.R. Murphy, S. Nath, S.T. Retterer, C.P. Collier, Controlling condensation and frost growth with chemical micropatterns, Sci. Rep. 6 (2016) 19131. doi:10.1038/srep19131.
[71] IEC 60529, Degrees of Protection Provided by Enclosures (IP Codes), Geneva Int. Electrotech. Comm. Ed. 2.1 (2001) 1–3. http://www.dsmt.com/pdf/resources/iprating.pdf.

Summary of articles

Summary of articles

Article I.

Passive Snow Repulsion: A State-of-the-art Review Illuminating Research Gaps and Possibilities

A first review of the published literature on the mitigation of snow adhesion, as compared to ice adhesion. It was found that snowphobicity, despite snow being a different and complex material, is often assumed synonymous with icephobicity or taken as a facet of icephobicity.

Article II.

Avoiding Snow and Ice Accretion on Building Integrated Photovoltaics – Challenges, Strategies and Opportunities

A thorough review of the physical challenges facing BIPV in cold climates. Known and proposed strategies for snow and ice impact mitigation are reviewed and related to the possible application to BIPV. Opportunities from successful mitigation designs and an evaluation of future research paths is also offered.

Article III.

A Gravity-Based Method for Measuring Snow Adhesion

Presentation of a novel technique for measuring snow adhesion in a reproducible fashion. A controllable environment along with realistic, synthetic snow generation allows the method to offer independently verifiable results. Limitations are discussed, backed by experimental results, and recommendations are made for future development of the method.

Article IV.

Snow adhesion on icephobic surfaces

Snow adhesion analyses were performed on known icephobic surfaces in order to relate snow and ice adhesion. It was found that low ice adhesion coatings are not necessarily accompanied by low snow adhesion but can in fact yield an increased snow adhesion relative to a reference material (in this case plain float glass). Possible mechanisms to explain the observed behaviour are discussed and recommendations for future explorations are made.

Article V.

Influence of glass surface roughness in the micrometre range on snow adhesion

Snow adhesion analyses performed on glass of varying roughness in order to investigate the impact of surface roughness on snow adhesion. Experiments were performed at -10°C to diminish any effect of liquid water lubrication. Surface roughness on the micrometre scale was imbued on glass substrates to isolate the roughness aspect of adhesion. It is shown that all roughness levels at this length scale dramatically raises snow adhesion to glass.

Article VI.

The adhesion of snow and ice – a classifying framework for engineering surfaces

In order to facilitate communication of requirements and results between interested parties, a classification scheme for mitigation of cold precipitation impact on engineering surfaces was suggested, based on the separation of ice adhesion from ice accretion and snow adhesion. The classification syntax was suggested in a way that express the performance of a surface in a concise and understandable manner.

Appendix A: Articles

I

Article I

Passive Snow Repulsion: A State-of the-art Review Illuminating Research Gaps and Possibilities

Per-Olof A. Borrebæk, Bjørn Petter Jelle, Zhiliang Zhang

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Passive Snow Repulsion: A State-of-the-art Review Illuminating Research Gaps and Possibilities

Per-Olof Andersson[a]*, Bjørn Petter Jelle[ab], Zhiliang Zhang[c]

[a]*Departement of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway*
[b]*Departement of Materials and Structures, SINTEF Building and Infrastructure, NO-7465 Trondheim, Norway*
[c]*Departement of Structural Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway*

Abstract

Building integrated photovoltaics (BIPV) are becoming more common every day. They are used everywhere, from the cabin in the mountains to the modern apartment building, and with more common use, strengths and weaknesses begin to reveal themselves more and more. In the regions of the world experiencing a colder climate, ice and snow coverage presents a challenge to productivity, BIPV resilience and longevity. Mechanically clearing snow and ice wears down the installations more quickly and may present a hazard to the people carrying out the clearing. Several research studies have been presented regarding the passive repulsion of ice and frost, while the repulsion of snow remains largely unexplored. This study aims to concisely present a review of what has been published in the field regarding snow repulsion and illuminate the research gaps and thus pave the way for future research. The snow aspect is illuminated by employing strategies previously applied to icephobicity research. A special emphasis is put on the comparison between microstructured, nanostructured and hierarchically structured surfaces as these constitute the basis of most icephobic (pagophobic) strategies.

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: Snow; Icephobic; Snowphobic; Frigophobic; Pagophobic; Chionophobic; Building integrated photovoltaics; BIPV; Microstructure; Nanostructure; Hierarchical structure; Review; State-of-the-art

* Corresponding author. Tel.: +47 92284661
E-mail address: per.olof.andersson@ntnu.no

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1. Introduction

Removing snow and ice from building integrated photovoltaic (BIPV) installations is a necessary step to maximize electricity production through the winter months in regions that experience significant snowfall. This is an activity that can be accompanied by a risk of personal injury (e.g. from falling off a slippery roof) and of damaging the modules with various tools. A BIPV solution with a surface that passively sheds snow would effectively eliminate this risk and ensure continuous production throughout the year. Also, the risk of irreversibly damaging an integrated part of a building envelope is potentially expensive to rectify, making the passive clearing of snow and ice that much more important.

A lot of recent work has been carried out in the field of passively de-icing surfaces [1–5] and the terms icephobic and pagophobic were invented to describe these surfaces. Passive snow repulsion or shedding, however, is a largely unexplored area. In this study, possible strategies are explored and recent research reviewed in order to illuminate challenges and future research opportunities. In keeping with scientific tradition, snowphobic surfaces will hereafter be referred to as chionophobic surfaces (chion = snow (Greek)).

2. Ice versus snow

While significantly different phenomena, ice and snow accumulation are intimately related. As reviewed in a previous study [6], ice will commonly accumulate via a liquid stage whether it be glace, frost or rime. This makes the successful application of a superhydrophobic surface, a realistic potential solution. Snow differs from ice in that it is comprised of an agglomeration of snow crystals, liquid water and air; all in varying relative quantities. This gives snow a wide range of physical characteristics depending on composition and ambient conditions. Snow crystals also come in a great variety of morphologies, ranging from simple hexagonal prisms to the more famous dendritic forms [7–10] (*see figure 1*). This further adds complexity to the range of physical behaviour snow can display.

Snow has been defined by Sojoudi et al. [3] as "dry" at temperatures below -1°C to -2°C and "wet" above the same. The same definition was previously made by Glenne et al. [11] but with a limit at 5°C and Pfister et al. [12] observed a limit of snow cohesion at -3°C. This implies some ambiguity as to what can be defined as "wet" and "dry" snow. A more stringent treatment could be as a continuum of compositions containing air, water and snow crystals (*see figure 1*). Each continuum will, however, only be valid for one crystal morphology and can be strongly affected by the level of inter-crystal bonding of the snow.

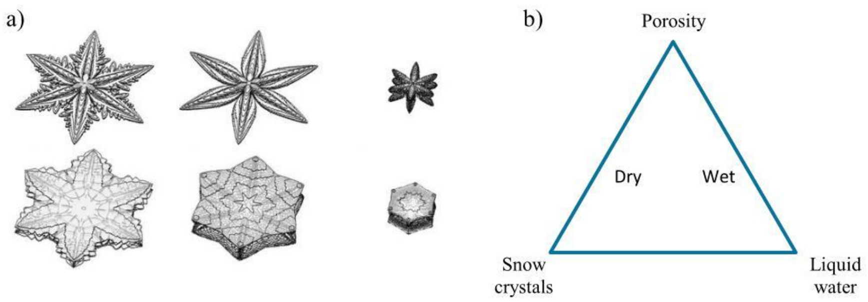

Fig. 1. (a) Snow crystal morphology examples as shown by Kelly et al. [10]; (b) Suggested compositional view of snow depicted as a ternary diagram, yielding a more dynamic definition of "wet" and "dry" snow. (The figure may appear to suggest the existence of porous water, which is incorrect. It is merely a representation of the coexistence of the three components)

3. Snow repulsion and shedding strategies

Snow crystals can have several hundred different types of morphologies depending on the thermodynamic conditions in the atmosphere at the time of their formation [8, 9]. This can make it very difficult to accurately predict the behaviour of snow in the general sense. In a previous study [6], strategies for preventing icing and the passive removal of ice were reviewed, but strategies catering specifically to the removal of snow and prevention of snow accumulation were largely omitted. In the following subsections, the most promising pagophobic strategies are reviewed with regards to chionophobicity and superhydrophobicity is given a special emphasis as the foremost promising pagophobic strategy.

3.1. Using superhydrophobic surfaces against snow

Similar to the accretion of ice, snow accumulation can be assumed to be aided by the onset of frost on a surface. Frost effectively alters the apparent surface exposed to the natural elements, to a rough, cold surface that is ideal for the adhesion and growth of ice, and likely snow as well. This speaks to the advantage of using a pagophobic strategy to achieve chionophobicity as well.

The porous nature of snow allows it to act as a thermally insulating material with thermal conductivity between about 0.04 W/mK [13] and 0.9 W/mK [14, 15] depending on snow density, water contents etc. This allows it to trap heat beneath even a very thin layer of snow. Andrews et al. [13] argue that this, in combination with the optical transparency of a thin snow layer, might be able to accumulate heat like a greenhouse, melting the inner most snow layer. The liquid water would then act as a lubricant at the interface to aid the snow in sliding on the underlying surface.

An obvious limitation of this strategy is the severely reduced transmission of solar radiation through thick layers of snow. At 2 cm of snow, the reduction is approximately 80% and at 10 cm, the reduction is 96% [13]. In locations that experience significant snowfall, the heating effect might be severely reduced, or even negligible, following a heavy snowfall event. It has, however, been shown that a superhydrophobic surface aids dry snow sliding off a surface and reduces the adhesion strength of both wet and dry snow. Unfortunately, the sliding of wet snow is not facilitated. Instead, a hydrophilic surface has been shown to accomplish this [16].

A potential explanation of this behaviour is the sliding lubrication of a water film formed at the interface by the attraction of the hydrophilic surface, whereas this film is rejected by the superhydrophobic surface, leaving the dry snow crystals in contact with the surface and thus hindering the sliding behaviour. The lowered adhesion of both kinds of snow to the superhydrophobic surface, could be explained by the lack of surface wetting lowering the adhesive bonding between any water contents and the surface. Very dry snow would naturally lack this adhesive effect, and could possibly be further aided by the reduced surface exposure offered by a nanostructured surface and/or the repelling effect between water molecules and a fluoropolymer.

3.1.1. Structured surfaces

There are, broadly speaking, three types of structured surfaces commonly associated with superhydrophobicity and pagophobicity. Microstructured, nanostructured and hierarchical surfaces. In the case of ice- and frost prevention and removal, the nanostructured and hierarchical structures have shown the most promise while microstructured superhydrophobic surfaces suffer from complete loss of pagophobicity at the onset of frost accretion within the structure [17].

Of these, the hierarchical surface has the potential advantage of reducing the effectively exposed surface area. This minimizes thermal conduction and friction, while allowing for the capturing of air beneath a falling water droplet, possibly allowing it to bounce on the surface without being pinned in a Wenzel state [1, 4]. A potential drawback of the hierarchical structure could be the physical hindrance of snow crystals from the micro-scaled structures. It is a possibility that dendritic crystals, for instance, get caught in some structure designs and hinder successful repulsion and sliding. Well controlled experiments could potentially elucidate this matter and present further possibilities of chionophobicity surface designs.

The strictly nanostructured surface could potentially serve as a compromise. It might lack the extra apparent surface reduction of a hierarchical surface, but has the advantage of increased smoothness. It might also offer a simplified production more suitable to large scale production. One could also imagine a hierarchical surface with preferential directionality in an obvious sliding direction, similar to the three-dimensional structures produced by Kako et al. [16].

3.1.2. Liquid infused surfaces

Liquid infused surfaces (LIS) still remain unexplored as chionophobic alternatives. Though they hold great promise as pagophobic surfaces, the liquid surface that so effectively retards frost formation and ice accretion [18] could potentially counteract the desired repulsion of snow by adhesive effects between the snow crystals and the liquid surface. By strategically selecting the lubricating liquid, however, this issue could be addressed and with sufficient experimentation, it might hold an important key to the successful repulsion of snow.

A related surface design is the slippery liquid infused porous surface (SLIPS) [19, 20]. The strategy of these closely resemble that of LIS surfaces but attempt to counteract the depletion of lubricating liquid by infusing it into the underlying material, allowing it to act as a lubricant buffer while counteracting depletion. There has been significant research conducted on these surfaces with respect to pagophobicity but not with respect to chionophobicity.

3.1.3. Smooth surfaces and hybrid surfaces

Other superhydrophobic approaches to pagophobicity include the use of smooth fluoropolymers, like polytetrafluoroethylene (PTFE) [21] or the hybridization of polydimethylsiloxane (PDMS) material with the SLIPS strategy [5]. These have shown very promising results as pagophobic materials and are interesting candidates for testing as chionophobic surfaces.

A more recent development, magnetic slippery surfaces (MAGSS), has been the application of a ferromagnetic superhydrophobic liquid to a magnetic surface, magnetized in a pattern to raise the liquid in a way that resembles that of a microstructured surface [22]. This surface has the advantage of self-healing and frost repulsion seen in LIS and SLIPS while being simultaneously smooth and structured. This allows for a reduction of exposed apparent surface area and, consequently, reduces the thermal conduction and friction. If this can be viewed as a passive surface could be debated, but it should not consume any of the electricity generated by the BIPV installation if permanent magnets are utilized.

3.2. Balancing repulsion of both wet and dry snow

The adhesion and sliding of snow on superhydrophobic and hydrophilic surfaces was evaluated by Kako et al. [16]. Both were found to be advantageous under different circumstances. The superhydrophobic surface was found to prevent adhesion of both wet and dry snow while facilitating the sliding of dry snow. The hydrophilic surface, on the other hand, was found to facilitate sliding of wet snow. This was then followed up by experiments where hybridized surfaces with both hydrophobic and hydrophilic elements were tested, showing, as could be expected, a behaviour close to the weighted average of the surface distribution [16].

These experiments have one significant point of critique, however. They used synthetic replacement for natural snow, consisting of water suspended porous glass beads. While this may simulate the viscosity quite accurately, the particle interactions with the surface and between the glass beads may not correctly simulate that of natural snow. The surfaces prepared for these experiments might behave quite differently when exposed to natural snow.

In addition to balancing the repulsion of wet and dry snow, there remains the need to repel frost and ice accretion as well. As the optimal strategies for each might differ, it could be that a compromise must be made. In such an event, it might be beneficial to tune the compromise to each application and location. A façade mounted BIPV solution might have a greater need for pagophobicity while a roof mounted BIPV system might have a greater need of strategies beneficial to chionophobicity.

3.3. Building integration for optimization of snow shedding

An advantage of BIPV installations is the great variety of integration that can be utilized. Photovoltaic (PV) panels can be applied on facades, roofs, ornamentations, in windows and so on. In urban locations with tall buildings situated in close proximity, the more advantageous placement might be on the roof, as this minimizes the shading. For such applications it might be possible to tailor the surface of the PV modules for the reduced sliding angle.

For buildings situated in a more spacious manner, it might be advantageous to place the BIPVs on the façade or incorporate them in the windows. This could be advantageous, not only to the shedding of snow and ice by the vertical surface, but could actually generate more energy in winter than roof mounted BIPVs [23]. Owing to the increased albedo effect of a snowy country, the façade could, despite the less optimized solar radiation angle, capture more solar radiation in the winter.

There might also be an angle, optimized for each location depending on expected albedo effects, at which a façade or roof might enjoy the maximized effect of both radiation angle and albedo effects while allowing for maximized sliding effect. This would then have to be considered from a net annual production standpoint to optimize the production economy of the installation and, as a result, the economy of the building.

Integration of PVs into buildings should thus start in the early stages of building design, as an integral part of the functionality of the building. This ensures sufficient power generation for the desired purposes, allows for a perfect fit of BIPV modules to building standards and the financial aspect of the installations is given more transparency to the commissioning party.

4. Future research opportunities

As mentioned previously, the superhydrophobic strategies applied to pagophobicity would be very interesting to evaluate with respect to chionophobicity. A comparison of the dry strategies (structured surfaces and fluoropolymer surfaces) to the wet strategies (LIS and SLIPS) would also be a very interesting aspect to have elucidated. It should, however, be performed with as realistic snow as can be managed, in order to deconvolute the effects of different snow types and different ambient conditions.

The mentioned combination of superhydrophobic and hydrophilic surfaces would also be of interest to further develop. Different geometries with different materials and strategies could be employed and focused in a way that optimizes the geometries to the applied surface orientation and application.

Another possibility for the future is the albedo effect. Acquiring quantitative evidence of how much this effect the energy production under different circumstances and possibly determining a method for predicting it, would be of great importance to future building integration strategies.

Aspects that have not been mentioned above, that would be of great interest to research further, include the following:

- Assess the thermodynamic albedo effects of a black backside of free-standing PV systems. It has been mentioned by Ross et al. [24] as a potential solution for freestanding PV installations.
- For each surface evaluated, there should be a minimum angle for snow sliding that can be calculated. This should also be combined with a comparison between snow types and ambient conditions.
- A closer assessment of the sintering and melting behaviour of snow would be interesting as this could potentially affect the sliding behaviour of snow in a significant manner.
- Avalanches have been studied for many years in the hopes of better understanding and predicting where and when they will occur. This research could potentially be adapted to the sliding of snow on engineered materials like roof tiles and façade mounted BIPVs.

5. Concluding remarks

Building integrated photovoltaic (BIPV) installations in countries with significant precipitation in the form of snow, experience a loss of energy production due to the physical obstruction of solar radiation by snow. The efficient removal of this snow remain a largely unexplored, yet very important, area. Herein, a concise summary of possible research topics and opportunities is presented along with a summary of existing research presented on the topic.

It appears evident that there is a wide range of topics to be studied and the benefits of a successful future strategy should be a strong motivator for funding the research. The field is closely related to pagophobicity with potential applications in areas like aeronautical, nautical and automotive industries, besides the significance to the growing BIPV industry. As such, chionophobicity could be of significant interest to these same industries as well as building segment manufacturers in general.

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References

[1] Dash S, Alt MT, and Garimella SV. Hybrid surface design for robust superhydrophobicity. Langmuir 2012; 28:9606–9615.

[2] Fillion RM, Riahi AR, Edrisy A. A review of icing prevention in photovoltaic devices by surface engineering. Renewable and Sustainable Energy Reviews 2014; 32:797–809.

[3] Sojoudi H, Wang M, Boscher ND, McKinley GH, Gleason KK. Durable and scalable icephobic surfaces: similarities and distinctions from superhydrophobic surfaces. Soft matter 2016; 12:1938–1963.

[4] Zheng L *et al.* Exceptional superhydrophobicity and low velocity impact icephobicity of acetone-functionalized carbon nanotube films. Langmuir 2011; 27:9936–9943.

[5] Zhu L, Xue J, Wang Y, Chen Q, Ding J, and Wang Q. Ice-phobic coatings based on silicon-oil-infused polydimethylsiloxane. ACS applied materials & interfaces 2013; 5:4053–4062.

[6] Andersson PO *et al.* A review of possible pathways for avoiding snow and ice formation on building integrated photovoltaics. Submitted for publishing 2017.

[7] Rango A, Wergin WP, Erbe EF. Snow crystal imaging using scanning electron microscopy: I. Precipitated snow. Hydrological sciences journal 1996; 41:219–233

[8] Gray DM, Male DH. Handbook of Snow, Principles, Processes, Managemnet and Use. New Jersey: The Blackburn Press; 1981.

[9] Magono C, Chung W. Meteorological classification of natural snow crystals. Journal of the Faculty of Science, Hokkaido University 1966; 2:321–335.

[10] Kelly JG, Boyer EC. Physical Improvements to a Mesoscopic Cellular Automaton Model for Three-Dimensional Snow Crystal Growth. Crystal Growth & Design 2014; 14:1392–1405.

[11] Glenne B. Sliding friction and boundary lubrication of snow. Journal of tribology 1987; 109:614–617.

[12] Pfister R, Schneebeli M. Snow accumulation on boards of different sizes and shapes. Hydrological processes 1999; 13:2345–2355.

[13] Andrews RW, Pollard A, Pearce JM. The effects of snowfall on solar photovoltaic performance. Solar Energy 2013; 92:84–97.

[14] Calonne N, Flin F, Morin S, Lesaffre B, du Roscoat SR, Geindreau C. Numerical and experimental investigations of the effective thermal conductivity of snow. Geophysical Research Letters 2011; 38.

[15] Riche F, Schneebeli M. Thermal conductivity of snow measured by three independent methods and anisotropy considerations. The Cryosphere 2013; 7:217–227.

[16] Kako T *et al.* Adhesion and sliding of wet snow on a super-hydrophobic surface with hydrophilic channels. Journal of Materials Science 2004; 39:547–555.

[17] Varanasi KK, Deng T, Smith JD, Hsu M, Bhate N. Frost formation and ice adhesion on superhydrophobic surfaces. Applied Physics Letters 2010; 97:234102.

[18] Kim P, Wong TS, Alvarenga J, Kreder MJ, Adorno-Martinez WE, Aizenberg J. Liquid-infused nanostructured surfaces with extreme anti-ice and anti-frost performance. ACS nano 2012; 6:6569–6577.

[19] Wong TS *et al.* Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity. Nature 2011; 477:443–447.

[20] Wilson PW *et al.* Inhibition of ice nucleation by slippery liquid-infused porous surfaces (SLIPS). Physical Chemistry Chemical Physics 2013; 15:581–585.

[21] Antonini C, Innocenti M, Horn T, Marengo M, Amirfazli A. Understanding the effect of superhydrophobic coatings on energy reduction in anti-icing systems. Cold Regions Science and Technology 2011; 67:58–67.

[22] Irajizad P, Hasnain M, Farokhnia N, Sajadi,SM, Ghasemi H. Magnetic slippery extreme icephobic surfaces. Nature Communications 2016; 7:13395.

[23] Yoshioka K, Hasegawa J, Saitoh T, Yatabe S. Performance analysis of a PV array installed on building walls in a snowy country. Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty-Ninth IEEE. 2002. P. 1621–1624.

[24] Ross MMD, Usher EP. Photovoltaic array icing and snow accumulation: A study of a passive melting technology. Proceedings of the 21st Annual Conference of the Solar Energy Society of Canada, Toronto, Ontario. 1995; 31:21–26.

II

Article II

Avoiding Snow and Ice Accretion on Building Integrated Photovoltaics – Challenges, Strategies and Opportunities

Per-Olof A. Borrebæk, Bjørn Petter Jelle, Zhiliang Zhang

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Avoiding snow and ice accretion on building integrated photovoltaics – challenges, strategies, and opportunities

Per-Olof A. Borrebæk [a,*], Bjørn Petter Jelle [a,b], Zhiliang Zhang [c]

[a] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), NO-7491, Trondheim, Norway
[b] Department of Materials and Structures, SINTEF Community, NO-7465, Trondheim, Norway
[c] Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), NO-7491, Trondheim, Norway

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ABSTRACT

As building integrated photovoltaics (BIPV) are becoming increasingly popular, the demand for optimized utilization will be increasing with respect to efficiency, aesthetics and reliability. In cold climate regions, we predict that there will also be a growing focus on how to avoid snow and ice formation on the exterior surfaces of BIPV. During the winter period there is substantially less incident solar radiation. This is also the period when the solar radiation is most needed for heating, lighting and power production purposes. The task to avoid accretion of snow and ice is challenging due to the fact that snow, ice and ambient weather conditions exist in countless variations and combinations. Snowfall, freezing of rain water and condensation of air moisture with subsequent freezing, are examples of aspects that have to be addressed in a satisfactory way. The present study aims to review the cold weather challenges facing BIPV, the strategies for overcoming them and the opportunities that follow from successfully overcoming them.

1. Introduction

With the ever-increasing number of installed photovoltaic (PV) systems, the demand for efficiency and aesthetics has risen as well. Seamless integration of photovoltaic panels in building skins is the next logical step in renewable energy production and investment in such products is quickly becoming more feasible. These integrated products are known as building integrated photovoltaics (BIPV) and have recently gotten increased attention due to Elon Musk's (known from Tesla, The Boring Company and Space X) investment in Solar City to start producing BIPV.

With a growing market comes the demands that installations produce electricity steadily over time, be reliable and yield a good return-of-investment (ROI). ROI will be significantly aided by the simultaneous investment in new roof cladding and electricity generating photovoltaics (PV) [1]. A corollary obstacle is evident in cold regions where snow and ice reduce production to zero very quickly [2–4]. It should thus be removed from PV surfaces in an efficient and timely manner. Current methods involve either manual labour, consumption of energy, or polluting de-icing chemicals [5].

As power production is lower in wintertime due to the low incident angle of light and increased atmospheric absorption, the potential gain of removing the snow must outweigh the added cost of the chosen solution. Melting of ice requires a tremendous amount of energy, cutting into the ROI while chemical de-icing strategies contribute to the environmental degradation and should thus be avoided [6]. Chemical de-icing is currently used in aeronautics as no viable alternatives exist [7]. Manual labour can be applied and vary in approach but common risk factors include personal injury (e.g. falling from a slippery roof) and risk of damaging the installation surfaces with various tools [8].

A proposed strategy that has been investigated the last few decades is to make the surface passively repel all ice formation in a similar manner to superhydrophobic surfaces repelling water. Some disbelief in the applicability of the concept exist, as frost accretion has been reported to effectively negate any ice adhesion reducing properties [9,10].

The term icephobic is commonly used and somewhat self-explanatory but still lack a formal thermodynamic definition. Depending on application, some studies focus on low adhesion strength between ice and a solid surface [11–14], some on the prolonging of freezing time of sessile or impacting water droplets [15,16], and others on the prevention of ice accretion [13,17]. Hejazi et al. have summarized these definitions with three conditions of icephobicity: Preventing the freezing of water condensing on the surface (frost), preventing the freezing of incoming water, and if ice is formed, it should have a low

* Corresponding author.
E-mail address: per.olof.andersson@ntnu.no (P.-O.A. Borrebæk).

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adhesion strength [18]. Kreder et al. [19] made a similar list of conditions: Suppression of ice nucleation, impeding frost formation and reduce ice adhesion forces.

In the definitions used for icephobicity, however, there is rarely an inclusion of the repellence or shedding of snow. This is possibly due to the difference in behaviour and characteristics of snow. Therefore, the term *snowphobic* (or more formally, pagophobic) is used to describe this [20]. While this term also lacks a specific definition, it can be expected to contain, at least, a minimization of adhesion to a hitherto undefined degree.

Icephobic and snowphobic surfaces carries significant potential for a cost-effective solution for BIPV and PV in general. In attempting to obtain such a surface that is adequate, reliable, and scalable, several strategies have been explored [21–24]. At present, none of the applications explored have seen widespread implementation. In this study, the challenges of snow and ice on BIPV will be reviewed along with strategies for overcoming them and the opportunities that follow from a successful designed system.

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 BIPV to, not only to produce electricity steadily and efficiently, but also to be chemically and mechanically stabile enough to withstand the rigors of weather and wind in a potentially harsh climate.

In some parts of the world, like the arctic and sub-arctic regions, icing and snow coverage is a real problem as snow coverage can remain during a significant part of the year [25,26], reducing the productivity in a region that has a lower incident light intensity [27]. In addition, ice and snow occur in numerous forms [28,29], and while one strategy might work adequately for the repelling of ice formed by supercooled rain, it might not be as effective in handling other forms of ice, e.g. frost, as shown by Varanasi et al. [10] and Rykaczewski et al. [24].

A successful design 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 ultraviolet (UV) radiation.

2.1. Ice and rime

Under natural terrestrial conditions, ice may form in a number of ways and may present a wide range of physical characteristics; from glaze ice to rime.

The formation of glaze ice occurs at moderately low temperatures and low to moderate wind speeds. This allows the water molecules the freedom of movement to establish equilibrated solid ice. As wind speeds increase and temperature decreases, rime ice begins to form. High wind speeds and rapid freezing due to low temperatures, forces liquid droplets to form miniature icicles in the leeward direction. This may sometimes appear similar to frost but rime consists of a thermodynamically stabile ice phase whereas frost maintains a non-equilibrium shape, similarly to snow.

These forms of ice accretion occur through solidification of liquid water such as impinging supercooled water droplets from rain or ocean spray [30]. This occur when the water droplets are at a temperature lower than the equilibrium melting temperature, sustained by the droplet curvatures (Gibbs-Thompson effect) and lack of heterogeneous nucleation sites [31]. These droplets then hit and conform to the host surface, changing the liquid-gas interface curvature and introduce a liquid-solid interface. This permits heterogeneous nucleation to occur and ice begins to accrete.

This kind of precipitation can result in loss of efficiency in PV- and wind power installation [4,5,8], hazardous icing of roads, break-down of power lines [19,32,33], and stalling aerofoil aircraft [34,35], just to name a few.

As the accretion of ice occurs primarily through the solidification of liquid phase water, an icephobic surface's ability to repel liquid water is crucial. Two things must be achieved to accomplish this: Minimizing the surface contact time by shedding the water before it has time to freeze, and reduction of the heterogeneous nucleation potential to allow for as much time as possible [17,19,21,36–38].

2.2. Snow

In the case of PV installations, a snow cover as thin as 2 cm can reduce the electricity generation by as much as 80% [2–4]. As snow is also the more common cold weather element to impact PV, it is of vital importance to address this issue.

Wet snow has a tendency to accumulate on almost any surface and is a well-known problem area for power lines and rooftops [39,40]. 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 may have the potential to reduce construction and maintenance costs.

Dry snow accumulates rather than accretes and forms banks of snow when wind is present. This stems from very different adhesion mechanisms from wet snow.

The mechanical properties of snow, and thus the interfacial sliding and adhesion mechanisms, continuously evolve and are difficult to predict. It depends on factors such as the morphology of the snow crystals, the liquid water content (LWC), the snow and substrate temperatures, the mechanical motion of the snow, and so on. Snow falling to the ground, forms as it falls through changing atmospheric pressures and temperatures to become the familiar flakes of snow.

Snow is commonly separated in two main categories depending on the liquid water content (LWC): 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. [41] suggest an approximate temperature limit of -1 or $-2\,^{\circ}$C, below which the snow can be considered dry, and above which it can be considered wet. A more continuous definition may be obtained through the dielectric constant of the snow, which can provide an estimation of the LWC [42–44]. For the present purposes, however, the simpler definition is utilized.

2.3. 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 through condensation [45]. 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 [21]. The droplets will stay in the liquid state until ice nucleation and growth occur, and the droplets freeze. The time required is theoretically dependent on the size and shape of the droplet (melting point suppression by the Gibbs-Thompson effect), the temperature of the water, the substrate and the atmosphere as well as the heat exchange rate with the surface and the atmosphere [21].

Condensation also occurs at night through radiative cooling of PV. This process is the same as with car windows frosting overnight, where heat energy stored in the car allows for more humidity close to the glass. As heat radiated up into space, the condensation forms and quickly freezes. The effects on PV installations (Fig. 1), however, is smaller due to the smaller amount of thermal energy stored in the solar panel compared to the inside of a car.

De-sublimation 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 [45]. 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 BIPV, the condensation process is the common and thus the more relevant aspect.

2.4. Physical wear

Besides precipitation, building elements must withstand physical wear in order to securely protect the integrity of the building. Traditional building elements adhere to strict national and/or international standards to ensure quality and safety. BIPV must also adhere to these standards, while simultaneously adhering to the standards of PV electronics.

Any design to combat frozen precipitation, be it passive or active, must likewise be resilient in order to preserve its functionality over time. This may present challenges to the design of coatings, surfaces and processes that must perform over extended periods of time in order to be financially feasible.

2.4.1. Hail

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

Created in the atmosphere at high altitudes, the impact velocity of hail is high and thus the potential for structural damage is 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.

2.4.2. Wind and UV radiation

Wind can be both beneficial and deleterious to the removal of snow and ice. It may aid in the shedding by added shear force or it may carry materials such as leaves, sand, insects and other soiling and abrasive contaminants. This has given rise to the self-cleaning glazing, which is also strongly considered for PV installations worldwide as soiling is a common problem.

UV radiation can have a deleterious effect on a sensitive surface. Polymer surfaces or polymer-based coatings are especially sensitive as they may suffer from UV photodegradation and decomposition. It is thus an important factor to bear in mind when designing surfaces and coatings.

3. Technical challenges

Cold weather precipitation can, as explored above, have a significant impact on BIPV installations. In addition to this, there are some technical challenges for ice and snow mitigation that should not be overlooked.

Fig. 1. Photo of frost accretion on common PV installation on a roof near Trondheim, Norway. Courtesy of GETEK Energy AS (Norway).

3.1. Shedding and retention of snow and ice

In countries with significant snow precipitation, snow is generally retained on roofs by means of snow guards as exemplified in Fig. 2. They are meant to prevent personal injury from snow and ice sliding off roof tops.

These devices are commonly mandatory by law and in attempting to design an ice- and snow-shedding surface for PV, this fact must be taken into account. If spontaneous snow and ice shedding is to be made real, the snow guards must be significantly redesigned or dispensed with entirely. This places requirements on the shedding surface to shed sufficiently small quantities that there is no risk of injury to any person below the roof. It must also do so consistently over time and regardless of weather conditions.

3.2. Snow accumulation due to confinement

PV installations are commonly installed in rows over the surface of a roof and at an angle optimized for solar radiation harvesting. This often yields a saw-tooth surface as seen in the installations in Figs. 1 and 3. The spatial confinement here yields a retention of snow at the base of the panels, preventing sliding of the snow. A successful ice- and snowphobic surface treatment is dependent on sufficient space for the snow and ice to fall away.

Likewise, it is often the case that snow begins to slide but catches on the frame holding the PV module laminate together, as discussed by Weiss and Weiss [46]. This leads to the conclusion that frameless panels are beneficial to the shedding of snow, as indicated by experiments [47]. An addition to this argument, would be that panels, frameless or otherwise, would have gaps between them where snow may catch. Applying BIPV to roofing often avoids this by slightly overlapping the devices in a staggered manner.

3.3. Transparency

As photovoltaics require the maximum amount of solar radiation possible to reach the surface, in the range of wavelengths absorbed by the PV cells, any coating material or surface treatment must be inherently transparent in this range. Fillion et al. [48] make just this point, focusing especially on coating materials, and cite some researchers that have managed to produce coatings with well above 90% optical transmission in certain wavelength ranges. As a contrast, the typical soda-lime float glass, commonly used in windows, has an optical transmission of less than 90% across the solar radiation spectrum [49].

Fig. 2. Snow guard. Photo of a snow guard holding snow on a residential roof in Trondheim, Norway.

Fig. 3. Photo of snow covered PV installation on a roof near Trondheim, Norway. Snow can be seen to have begun to slide but has been hindered due to build-up. Courtesy of GETEK Energy AS (Norway).

3.4. Durability

Any coating or surface treatment must be able to last a substantial part of the modules expected life time. Warranty of photovoltaics is a complex matter as it encompasses several aspects, such as PV modules, inverters, workmanship etc. For the present purposes, we consider the PV modules only, as only those pertain to surface designs or coatings.

Larger PV producers often offer a warranty up to 25 years on the PV modules [50]. The net cost of a solution increases the more frequently re-application of a coating or processing of the surfaces must be carried out. A spray-on solution may allow for more frequent re-applications, while direct surface engineering may not allow for any re-application at all. The question of durability is thus closely linked to the method of application and costs, making proper guidelines difficult to estimate. As noted by Heinstein et al. [50], psychology also plays a major role, further complicating matters.

Surface designs intended as ice- or snow-phobic are practically never tested for long-term stability by e.g. accelerated ageing, though some are tested for stability through time-consuming icing and de-icing cycling, typically 10–30 times [51,52]. This makes it difficult to estimate a technical life expectancy for new designs.

3.5. Price

For a surface design to be successful on the market and thus provide an applicable solution to the problem of ice and snow, the solution must be cost effective. The financial losses due to snow and ice on BIPV, however, are difficult to assess properly due to the varying conditions of the installation sites, variation in price on electricity, etc.

Attempts at estimating energy losses have been made, though conclusions vary [2,4,53,54]. The most in-depth analyses located for the present review, and nearly concurrently published, Andrews et al. [54] and Marion et al. [53] placed losses between 1-3.5% and 1–12% respectively. Of these, only Marion et al. presented error estimation from a model; their model fall within 0.5–1.5% (absolute) of measurement losses [53].

While as small an error as possible between model and measurement is desirable, these studies are case studies, applicable only to the circumstances where they were performed, and should thus be considered with some care. They do, however, provide estimates to base further estimations of financial impact. This is explored by Andrews et al. [54], who arrive at a lowering of the return on investment (ROI) of 0.56–0.60% (absolute) as a direct result of snow coverage [54]. For that specific case, there may thus be little motivation to invest in advanced methods for snow- and ice management.

3.6. Application and re-application

Assuming a non-permanent surface modification, any chosen design must be easy to apply. Not only is it a matter of expense versus gain, but also one of practicality. Re-applying a coating, e.g. on BIPV façade elements in a multilevel building, may be hazardous, costly, and time consuming. Fig. 4 exemplifies such a challenge. Thus, the more resilient the surface modification is, the more versatile it will be.

Naturally, the cost of application is an important factor, as every re-application required over the BIPV installations lifetime, increases the demands for energy loss reduction.

Fig. 4. Oseana cultural center with BIPV on a combined roof and façade [55].

4. Mitigation and prevention strategies

There are many proposed strategies for mitigation and prevention of ice and snow accretion. The present section aims to present and contrast these strategies without exploring their full depth individually, as they each may warrant an extensive review to do so properly.

Mitigation of ice and snow, is most commonly based on superhydrophobicity, although some designs have been proposed using hydrophilicity [23,56–58]. The present section will briefly explore superhydrophobicity to provide context for the snow and ice mitigation strategies. Hydrophilicity is largely omitted in the present review due to the specific requirements of snow and ice mitigation commonly being better served by superhydrophobicity, as explored below.

4.1. Superhydrophobicity

Hydrophobicity is the result of the relation between interfacial free energies (often simply referred to as surface energies) between the three phases present: Solid, liquid, and vapour. Classically described by Young's equation

$$\cos\theta = \frac{\gamma_{sv} - \gamma_{sl}}{{}_{lv}} \tag{1}$$

where γ_{sv}, γ_{sl} and γ_{lv} are the interface energies between the three phases, solid, liquid and gas, and θ the contact angle (CA).

For structured surfaces, this formulation has been supplemented by the works of Wenzel [59] and Cassie and Baxter [60]. They describe two different states of wetting with equations (2) and (3) respectively.

$$\cos\theta^* = r\cos\theta \tag{2}$$

where θ^* is the resulting contact angle and r is the roughness ratio, and

$$\cos\theta^* = r_f f\cos\theta + f - 1 \tag{3}$$

where r_f is the roughness ratio of the apparent surface area and f is the fraction of contacting surface area.

The term *superhydrophobic* generally implies that CA exceeds 150°, though the phenomenon *para-hydrophobicity* may confuse matters. Parahydrophobic surfaces imply a surface that allows for CA above 150°, while droplets also adhere to the surface at high angles of tilt [61]. Therefore, the term superhydrophobic also carries an implication of low sliding angle of a droplet.

The sliding angle of a droplet is commonly omitted and instead a demand for low contact angle hysteresis (CAH), as described by

$$CAH = \theta_{rec} - \theta_{adv} \tag{4}$$

where θ_{rec} is the receding angle and θ_{adv} is the advancing angle. A formal definition of CAH required for superhydrophobicity has eluded the authors of the present review, however, it is typically no more than a few degrees [62,63].

4.2. Icephobicity

As previously discussed, icephobicity is commonly seen as having three main approaches: (i) denying ice the opportunity to nucleate from humid air and form frost, (ii) delay the nucleation long enough for water to be shed before ice forms and (iii) minimizing the adhesion strength of ice that has nucleated and attached to a surface. While not necessarily mutually exclusive, they are commonly treated separately in an effort to better focus the research.

4.2.1. Water shedding

Rainfall on sub-freezing surfaces and supercooled rain, are common occurrences in cold climates. In order to minimize the probability of water freezing on the surface, a surface can be designed to shed the water faster than the time it takes for nucleation and growth to occur [15,17,19]. This is commonly achieved through superhydrophobicity, which allows water impacting droplets to roll off [64,65] an inclined plane or even bounce [66,67].

As supercooled rain falls on a surface with a terminal velocity around 9.4 m/s [68], surfaces must be designed to disallow pinning of the water droplets and instead promote rolling or rebounding [66,67,69]. Conventionally, superhydrophobic surfaces have been assumed to accomplish this best, but it has also been noted that this might not always be the case [70]. For droplet roll-off, however, superhydrophobicity appear to remain the best option. Thus, care must be taken to select a surface design that will promote the rebounding of supercooled rain droplets without a significant risk of pinning.

Making a surface superhydrophobic does not only allow water to be shed quickly, but also prolongs the time required for the water droplets to freeze [15,21,70–72]. This is argued to be owed to a combination of liquid-to-solid thermal conduction [21], liquid-to-air convection [62], and radiation, where thermal conduction is a major heat transfer vector.

4.2.2. Ice droplet shedding

Similarly to water shedding, some researchers found that droplets that are not shed in the liquid state, may still be dislodged and shed in their frozen state [31,73,74]. Schutzius et al. [75] demonstrated dislodging so violent that it launched the frozen droplets several millimetres from the surface. They argue that this is a result of rapid vapour pressure increase under the droplet, owing to the rapid vaporization occurring in the freezing process, producing an overpressure under the droplet. Graeber et al. [73], tested this hypothesis specifically and found droplets to dislodge on substrates that disallow large vapour pressure gradients under the droplet. They argue that the key to self-dislodging of freezing droplets, is in the dynamics of solidification; specifically that the droplet freezes such that the droplet-substrate interface solidifies last [73]. They also provide evidence suggesting that thermal conductivity between droplet and substrate should be minimized to achieve this and argue that minimizing substrate thermal diffusivity and droplet-substrate contact area is vital to achieve this.

4.2.3. Frost denial

Another approach is to disallow the formation of ice through intelligent surface design. In order to understand how to prevent ice from nucleating on a surface, it is important to acquire an understanding of the nucleation process.

There are two main types of nucleation: Homogeneous nucleation and heterogeneous nucleation [76]. These describe the thermodynamics of condensation of a gas and solidification of a liquid; in this case, water vapour and liquid water. The former describes the process of water freezing in a theoretically infinite volume of pure and homogeneous body of liquid water. The latter takes into account the existence of an interface between a solid surface, a body of water (commonly a droplet) and the forming solid phase.

In practice, heterogeneous nucleation occurs at a higher temperature than homogeneous, making the influence of the substrate surface energy of substantial importance. Minimization of surface energy allows for a shift of the nucleation towards the homogeneous extreme and most strategies for attaining icephobicity therefore start with superhydrophobicity [31,77].

No surface design has yet been presented that will prevent water from freezing indefinitely. It can, however, delay and supress the heterogeneous effect and force the nucleation towards the homogeneous region.

As frost commonly forms through condensation, researchers have noted that frost occurs within the structures of some superhydrophobic surfaces [9,10]. This occurs as condensing droplets are small enough to fit within the structure and freeze there, without the opportunity to be removed through superhydrophobic shedding.

Suppressing the nucleation of ice in a water droplet, however, can be further aided by droplet size constraint as a result of the Gibbs-Thomson effect [76,78,79]. With sufficient confinement, it is therefore possible to force coalescence and shedding of the condensing water (Cassie condensate) before it has an opportunity to freeze [17,78,80]. A schematic representation of the Cassie condensate formation process can be seen in Fig. 5.

4.2.4. Ice adhesion minimization

A commonly explored option is to accept some accretion of ice. The mass of the ice itself, combined with very low interfacial adhesion, is then used to allow the ice to be shed periodically by means of gravity or other forces, be they naturally occurring (e.g. wind) or application specific (e.g. rotation of wind power turbine blades) [7,81–83].

There are several facets of ice adhesion that are often researched individually. Herein, we explore them in the same manner, and include a discussion on the measuring methodologies, as there are many and often yield different results.

4.2.4.1. Wettability. Minimization of adhesion can be approached in

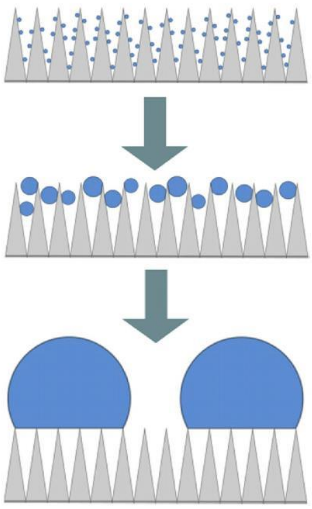

Fig. 5. Schematic representation of the principle of condensation expulsion through confinement as the droplets coalesce.

several ways. A common topic is that of the role of wettability [11,52, 84–86]. Stemming from the reversible free energy required for the creation and destruction of interfaces, Meuler et al. [11] previously found a correlation with the practical work of adhesion, scaling with [1 + cos θ_{rec}], where θ_{rec} is the receding contact angle [11]. This correlation, however, apply only to adhesion strengths above 100–150 kPa [11, 87].

Janjua et al. [52], however, showed a clear relation between ice adhesion and CAH, as defined by equation (4). This corroborates the conclusions of many studies [84,88], and they argue that Meuler overlooks aspects such as encompassing the full range of receding contact angles and statistical representation [52].

As one of the most explored design strategies to attain ice- and snowphobicity, a vast number of superhydrophobic surfaces have been designed and tested by various means, under various circumstances [15, 41,51,66,71,78,89–93]. Results often vary but most agree that wettability plays a major role in the adhesion, although to what degree, under what circumstances, is not clear. A full review of the role of wettability in ice adhesion exceeds the scope of the present study.

4.2.4.2. Stress concentration. Wetting as described by contact angle or contact angle hysteresis, does not necessarily correlate to adhesion strength. Other factors must be accounted for, as noted by several researchers [89,94–96]. Crack initiation and stress concentration are often cited as possible contributors, especially on structured surfaces where adhesion may be focused at several small points, rather than over a continuous surface [95,97]. Fortin and Perron [95] modelled ice adhesion with respect to shear stress, predicting a minimum ice adhesion when the surface consists of infinitely sharp points, high enough to minimize electrostatic forces, and with strength enough to maintain these over many de-icing cycles [95]. This may be the optimization of a model and not necessarily implementable but is very instructive in the importance of stress concentrators to reduce ice adhesion.

Making use of a surface design to induce crack initiation has thus been the main goal for several researchers [51,89,96]. Owing to the ridged nature of ice, surfaces may be designed in a manner that introduces stress concentrations in the interface dynamically [51,89]. This allows for cracks to be initiated that will then propagate quickly across the interface, releasing the ice.

4.2.4.3. Substrate material properties. The intrinsic properties of the material in contact with the ice may also have a significant influence on adhesion. Hydrogen bonding is often cited as the main bonding form between substrates and ice [98–100], but other factors may also be significant.

The quasi-liquid layer (QLL) shown to exist on ice [101,102], carry unbound water molecules able to induce electric charge mirroring in a substrate material. The mirrored charges then experience a coulombic attraction, commonly known as an image force, which relates to the surface materials permittivity. By testing substrates coated with materials of different dielectric constants, Saleema et al. [103] could show a significant influence of dielectric constant, although very low values seem to be required in order to substantially influence adhesion. A similar study by Ryzhkin and Petrenko [99] seems to corroborate the existence of this influence.

Petrenko [98] showed that the dynamic friction between ice and a substrate is affected by an applied electrostatic charge and, although this is a dynamic system and may translate poorly to statics, it further illustrates the sensitivity of ice to electrostatics.

4.2.4.4. Measuring ice adhesion. Ice adhesion is commonly tested on a small ice sample, typically on the scale of a few cm [89,104,105], and yields a measurement that has thus far seen widespread acceptance. Golivin et al. [96], however, recently found a size discrepancy when testing ice adhesion through mechanical push testing on samples up to 1 m in length. Up to a certain sample length, the common shear model predicted the results with acceptable accuracy. Above this length, however, no additional force was required to dislodge the sample. Thus, they argue, the currently accepted model incorrectly predicts ice adhesion of application size samples. They also conclude that surface designs commonly not accepted as icephobic may yield a lower adhesion strength for large areas [96]. They also propose a new model to complement the common adhesion model, for samples larger than a critical size that relates to the elastic modulus of ice.

Measuring ice adhesion in the common manners, like centrifugal adhesion testing (CAT) or force probe measurements, has generally seen some criticism of late [104,106,107]. Work and Lian [104] recently published an in-depth critical review of ice adhesion testing methodologies, citing several systemic problems with widely accepted practices. Generally, they cite problems such as lack of completeness in reported data (surface feature analyses, wetting characteristics, ice formation conditions, strain rate, evaluation of stress concentration, etc.) and how little awareness there appears to be of the complexity of ice adhesion testing [104].

4.2.4.5. Ice types. The manner in which ice is generated has been explored as an influence on ice adhesion strength by Rønneberg et al. [108]. They explored three categories of ice: precipitation ice, in-cloud ice, and bulk water ice (glaze ice approximate). Precipitation ice was found to adhere around 170% more strongly than glaze ice and around 47% more strongly than in-cloud ice. Several possible influences were cited: Ice microstructure, density, and the mechanical stiffness of the ice. They also rejected ice adhesion based on electrostatic interactions and QLL as these models predict behaviour trends in direct opposition to their observations [108].

This is an important point to explore as it evidently affects the adhesion quite significantly. While not explicitly explored, it may be of interest to consider that ice adhesion could appear to be reduced with increasing density due to an increased probability of interfacial crack initiation and propagation. This would be consistent with the correlation of increased grain size with increased stress concentration and ice stiffness, cited by Rønneberg et al. [108]. This could then be indicative of the observed correlation being a result of interfacial mechanisms which in turn depend on the properties of the ice, rather than a direct correlation to the intrinsic properties of the ice itself. If so, this study would not only show the important difference in adhesion between ice precipitation modes, but may also suggest that some types of ice adhesion mitigation may be better approached by strategies other than interfacial crack mechanics.

4.3. Snowphobicity

Snow falls onto surfaces in an already frozen, or partially frozen state and can thus not be repelled prior to formation. Snowphobicity, therefore generally refers only to the lowering of adhesion to the surface, optimally to the point where a small tilt angle or slight breeze is enough to remove snow continuously as it falls [4,5,20].

4.3.1. Snow adhesion minimization

The volume of published work on the adhesion strength of snow is, relative to that of ice, quite small and no generalized models have been developed. The primary body of work appear to be focused on predicting the accretion on overhead power-lines [39,109,110] or shedding from the same [40].

Specific focus on surface engineering for general snow adhesion minimization was evaluated by Kako et al. [23] and Andrews et al. [111].

Kako et al. [23] investigated the adhesion strength of wet snow, using the herein adopted definition, as influenced by surface wettability. They concluded that superhydrophobic surfaces yield a reduced adhesion strength than other alternatives.

Andrews et al. [111] tested hydrodynamic surfaces with an *in-situ* method and conclude that no positive effect can be seen from merely hydrophobic coatings. Publications on similar testing of dry snow adhesion have eluded the present authors.

The snow wetness dependency of adhesion has not been properly explored. Some have explored the extremes of wet and dry, but no apparent explorations where wetness (or LWC), has been seen as a continuum.

Generally, snowphobicity appears grouped with ice adhesion and assumed to be a sub-set of icephobicity [41], though specific comparisons seem not to have been published, making the assumption open for debate and makes the adhesion of snow an excellent candidate for further study.

4.3.2. Measuring snow adhesion

Measuring snow adhesion cannot be carried out by common ice adhesion measurement techniques, such as force probe, CAT, etc., due to the high deformability of porous snow [112]. Snow adhesion is instead, commonly tested by allowing snowfall (natural or simulated) on fixed-angle installed test samples (Fig. 6) while monitoring aspects such as how much snow accumulates prior to shedding [113] or how much solar radiation is transmitted [111].

4.3.3. The relation to ice

The adhesion of ice and snow is naturally linked due to the shared origin (water) of the substances. The same processes are thus expected to contribute to the adhesion, albeit with possible differences in distribution. Ice and snow are, however, very different materials morphologically [114], mechanically [112] and thermodynamically [115]. Thus, what may make a surface icephobic in adhesion and/or accretion, does not necessarily make it snowphobic.

Successful snowphobic surfaces will likely also require some aspects of icephobicity. Frost denial and water shedding should be included as either occurrence of frost or glaze ice will negate the effects of any surface design for snow adhesion minimization. Specific ice adhesion minimization, or ice shedding effects, however, are not strictly necessary if all other aspects are fulfilled, though it may follow from the inclusion of the other aspects.

4.4. Active mitigation strategies

4.4.1. Chemical treatment

The aeronautics industry actively de-ices both commercial and military aircraft by means of chemical spraying. This is the only approved technology to date, for these applications, as the demands to be met are very high and the burden of proof weighs heavily before a passive solution can be implemented.

The chemicals used for de-icing have, however, been found detrimental to the environment [6,116] and represent a significant cost in maintaining aircraft [117]. These limitations would also affect any use on BIPV and demand regular re-application to keep the installation clear of snow and ice. Use of environmentally detrimental chemicals in close proximity to places of residence and work may also be subject to more stringent regulation. Thus, the costs may outweigh the benefits.

Application of brine or salt, as is often applied to pavement, may degrade a PV module [118] and would likewise require regular re-application, thus making it costly over time and increase demand on maintenance.

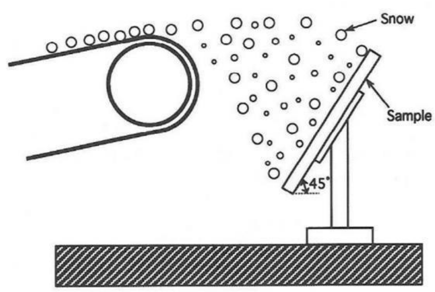

Fig. 6. Schematic of snow adhesion measurement setup by Saito et al. (1997) [113].

4.4.2. Surface heating

Heating solar panels to remove ice and snow has been tried, to generally positive effect [46,47,119,120]. While often questioned as to whether it is energetically favourable or not, a recent study suggests that it is possible to balance the cost of heating with gained production, given proper system design and regard for weather forecasts [119].

There are two main approaches to heating a module: Resistive heating cables placed behind the modules [47], or biased solar cells that produce resistive heating within the cells themselves [46]. Both methods show the desired effect of inducing sliding of snow by melting of the interfacial snow. Adding dedicated resistive circuits to a module will increase the already high cost of snow removal, possibly past the point of benefit.

Combination of heating and surface treatments/designs such as superhydrophobicity, could further the sliding of snow and ice, allowing the heating energy to be minimized. One such design was tested by Wang et al. [120], exhibiting ice accretion prevention down to -14 °C without the aid of electric heating, and down past -30 °C with a current applied to the conductive coating [120].

4.4.3. Mechanical systems

Ultrasonic de-icing has been tested for the aeronautics industry as well as the energy sector, specifically on wind power turbine blades and airborne transmission lines [121,122]. The technology has not yet been widely implemented though and is speculated by some to potentially be detrimental to a PV module [123], though this has not been shown.

Some have experimented with using cleaning robots for PV installations, though primarily for dust and sand clearing [124,125]. Such robots could, in theory, also be used for clearing snow from a surface, while also cleaning it. Cost of implementation, however, would be likely to exceed the benefits for household BIPV and may be better suited for industrial sized PV complexes.

5. Opportunities

5.1. Annual production increase

Successfully removing snow and ice in a cost effective and timely manner may allow for a significant production increase, making the installation of BIPV more attractive in regions where snow and ice may cause concern. As shown by Aarseth et al. [119], it is indeed possible to increase the annual production sufficiently to offset some costs, though how much may be a matter of local weather conditions, as pointed out by Pawluk et al. [126]. In some regions one may only add 1–3% to the annual production [2], while more snow rich regions, be it due to altitude or latitude, may yield >15% more energy produced per year [127].

5.2. Cold region synergy effects

It is widely recognised that PV should be kept cool in order to optimize production efficiency, making cooling of PV installations a topic of research in warmer regions [128]. Though the irradiation in colder regions may be smaller, the efficiency is thus better optimized.

In addition to better utilization of device efficiency, increased albedo from the highly reflective surfaces of snow, ice, and water, can increase production [129]. Thus, implementation of BIPV that optimizes the use of albedo effects from, e.g. nearby snow-covered fields, bodies of water, or glaciers, may exhibit a higher than expected production [129].

The net annual production in snow rich countries is unlikely to ever reach that found closer to the equatorial region. This, however, does in no way preclude the implementation of BIPV [130,131].

5.3. Surface design synergies

As most surface designs for snow and ice mitigation are based on superhydrophobicity, coupled with the often suggested design requirement of surface structuring to accomplish this, it may be possible to design a snow- or ice-shedding surface that bears a synergistic benefit to BIPV. Self-cleaning [132,133], anti-fouling [133], or anti-reflection [132] are examples of added effects that would benefit BIPV greatly and carry some similarities with common surface designs.

5.4. Nationally distributed energy production

Modern society is vitally dependent on electrical power for everything from pumping water and transportation of food and fuel, to medical facility functionality. Widespread power loss can thus have devastating effects when communities are cut off for prolonged periods [134,135]. It has also been rated in 2014 as one of the likeliest national threat scenarios by the Norwegian Directorate for Civil Protection [136].

Emerging technologies, such as smart grids and smart cities, may be combined with BIPV and other renewable energy sources to form subgroups of energy production, often referred to as *islanding* [137]. Though some industry may require massive amounts of energy, most life sustaining functions, like communication and food storage, require relatively little energy. Properly controlled, isolated regions could thus use their local energy production to maintain vital functions until the national grid is repaired, and main power restored.

5.5. Improved shedding from tilted surfaces

As previously discussed, PV modules usually have gaps between the modules even if they are frameless, e.g. in building applied photovoltaics (BAPV). This may cause snow and ice that has begun to slide, to catch and accumulate until melted. BIPV commonly circumvents this problem, either by design or fortunate coincidence, by applying the elements with a slight overlap in a staggered fashion and without the, otherwise familiar, aluminium frame. A successfully designed shedding surface will thus be aided by the application to BIPV, provided this overlapping design is adhered to, over that of the more common BAPV modules.

6. Future research opportunities

6.1. Application based classifications

Presently, there is a standard for de-icing liquids used by the aeronautics industry, denoted class I through IV, indicating performance as determined by how long it will remain effective. As previously mentioned, icephobicity and snowphobicity have no precise classification yet. This is owed in large part to the wide range of applications requiring different levels of repellence.

To this end, it may be beneficial to flip the problem around and produce a classification based on absolute values, to which applications can then claim their requirements. Aeronautics, which is a particularly demanding industry, could for example demand an ice adhesion level below 100 kPa, which is commonly recognised as icephobic for this very reason. Though, as indicated by recent findings [96], using an adhesion measurement in this manner may end up being misleading, as previously discussed.

One may envision a definition of icing- and frost retardation above X hours at Y % relative humidity and –Z °C. If Y and Z are predefined in a standardization, the classification reduces to a single number (X) indicating how long time one requires for the specific application.

6.2. Interfacial bonds

Dry snow is a very deformable and porous material that generally does not allow for a continuous propagating interfacial crack to dislodge it from a surface, the way that solid ice can (Fig. 7). It should then follow that other factors must be focused on in minimizing snow adhesion.

As previously discussed, hydrogen bonds are commonly accepted as the main contribution to direct interfacial and electrostatic image forces have been shown to have an effect on adhesion strength [98–100,103,138]. Despite this, most research appears to be focused on different ways of making surfaces superhydrophobic. Exploring ways of reducing the interfacial bonds, e.g. by manipulation of the dielectric properties of the materials, may unlock new venues to reduce adhesion of both ice and snow. Although snow may be more benefited as there is little possibilities for inducing crack propagation at its interface, ice adhesion may also benefit.

6.3. Interlocking on structured surfaces

When designing superhydrophobic surfaces, it is generally accepted that structuring at some level is greatly beneficial. Application of such a structured surface, however, may cause mechanical interlocking with dendritic snow, increasing the adhesive potential. Despite this, there has been little specific research on the matter. One may, for example, test otherwise identical surfaces with varied degrees of roughness and roughness orientation, along with varied snow microstructure.

6.4. Combining surface design and heating

Combining various surface designs with heating and make use of existing solutions to obtain sufficient ice and snow repellence, may allow for an application ready solution. Cost minimization will naturally be a significant driver in design and material selection, and margins can be small. This may have led to some disbelief in this solution and may be a contributing factor to the apparent lack of research on the topic.

7. Discussion

There are numerous approaches to mitigation of snow and ice accretion on BIPV, and indeed surfaces in general. Most seem to agree that superhydrophobicity alone is not a sufficient solution, but that it significantly contributes to reaching this goal.

Compelling arguments for new views on the modelling of the interfacial ice adhesion have been presented recently. Here superhydrophobicity is not central, but rather expanded upon, and should be explored further. Likewise, the influence of surface chemistry and the

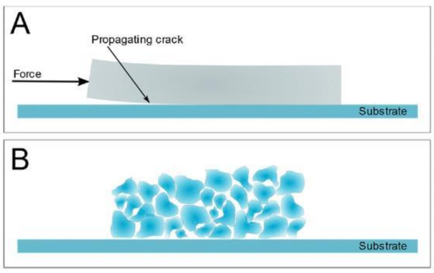

Fig. 7. Schematic representation of the interface between (A) substrate and continuous solid ice, and (B) substrate and snow.

direct interfacial bonds between ice and substrates have gotten some increase in attention, though this research facet is far from exhausted.

Avoiding ice and snow on a BIPV system is a highly complex matter, as the present review indicates. Each of the topics presented herein is significantly more complex than the present scope allows, and the reader is directed to the literature for a better in-depth understanding and analysis of specific topics.

The complex differences between snow and ice suggest an application-based approach might be advisable in pursuing ice or snow mitigation. In the case of BIPV, snow and frost are more common occurrences and should thus, in our view, be prioritized for this application. Pursuing these aspects will, in turn, be reliant upon defining some parameters that are to be achieved, e.g. a critical temperature and relative humidity that should/must be sustained frost free, or a maximum accretion depth of snow that can be allowed and for how long. This, as discussed, suggests a method of classification that would allow for a more precise discussion and better focused research.

The passive mitigation of snow and ice is a fascinating possibility that could, and perhaps realistically should, be combined with some active measures in order to function sufficiently reliably. Balancing cost and benefit will naturally be of vital importance, though it has been indicated that there are significant opportunities here for further exploration and optimization.

BIPV annual production efficiency is central in any cost-benefit analysis. Passive solutions require some surface modification and may impact productivity to some degree, through reduction of transmittance. Active mitigation strategies, on the other hand, are all energy consuming in some sense but do not directly impact the productivity of the BIPV system in the short term. Whatever the strategy, cost-influencing optimizations must be carefully considered.

Cost is always a driving factor and producing reliable solutions that improves ROI of BIPV will likely be key. To this end, the durability and price of a chosen solution will largely determine if a solution sees widespread implementation. As noted previously, ROI varies with location through the variation in climate and therefore the applicability of solutions will likely be location dependent.

There are some extreme locations where an ice- or snow-phobic surface will not suffice, and an active method may not be realistic. Fig. 8 shows a remote communications station on a mountain top in Norway. The combination of high altitude and latitude makes ice accumulate to the point where parts of the station have to be chiselled out in order to function.

Avoiding the accretion of snow has not been explored as much as the accretion and adhesion of ice and will likely require significant research to accomplish significant mitigation in a reliable way that can withstand the rigorous demands BIPV places on it.

8. Concluding remarks

The present review seeks to present the challenges faced by BIPV with a heavy focus on snow and ice accumulation, known strategies for overcoming them, and the possibilities afforded by successfully overcoming them. Closely related themes are also touched upon in order to form a more complete picture. Several subtopics presented herein are quite complex matters and warrant full reviews themselves to fully explore them.

Snow and ice still present a significant challenge in several areas, including BIPV. Depending on common icing conditions, an all-in-one solution appears unlikely to present itself. Instead it may be useful to focus on application specific solutions. To this end it may be useful to finally give icephobicity and snowphobicity proper definitions that may be sectioned in levels. Such a definition would allow for more focused research and a more precise discussion of the topic.

One of the most promising solutions for BIPV, that may be implemented today, is a combination of active and passive mitigation. E.g. heating combined with superhydrophobicity.

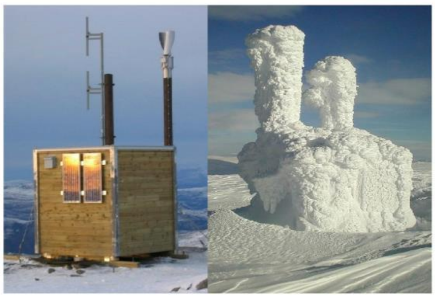

Fig. 8. Extreme ice and snow accumulation on a communications station, before (left) and after (right) accumulation. Courtesy of GETEK Energy AS (Norway).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] A.S. Bahaj, P.A.B. James, M.F. Jentsch, Photovoltaics: added value of architectural integration, Proc. Inst. Civ. Eng. Energy 160 (2007) 59–69, https://doi.org/10.1680/ener.2007.160.2.59.

[2] R.W. Andrews, A. Pollard, J.M. Pearce, The effects of snowfall on solar photovoltaic performance, Sol. Energy 92 (2013) 84–97, https://doi.org/10.1016/j.solener.2013.02.014.

[3] Å. Skomedal, The Transmittance of Light through Snow; an Initial Study for Solar Energy Systems, Physics, Norwegian University of Science and Technology, 2017, https://doi.org/10.13140/RG.2.2.10539.54568.

[4] E. Andenæs, B.P. Jelle, K. Ramlo, T. Kolås, J. Selj, S.E. Foss, The influence of snow and ice coverage on the energy generation from photovoltaic solar cells, Sol. Energy 159 (2018) 318–328, https://doi.org/10.1016/j.solener.2017.10.078.

[5] B.P. Jelle, The challenge of removing snow downfall on photovoltaic solar cell roofs in order to maximize solar energy efficiency - research opportunities for the future, Energy Build. 67 (2013) 334–351, https://doi.org/10.1016/j.enbuild.2013.08.010.

[6] L. Fay, X. Shi, Environmental impacts of chemicals for snow and ice control: state of the knowledge, Water Air Soil Pollut. 223 (2012) 2751–2770, https://doi.org/10.1007/s11270-011-1064-6.

[7] O. Parent, A. Ilinca, Anti-icing and de-icing techniques for wind turbines: critical review, Cold Reg. Sci. Technol. 65 (2011) 88–96, https://doi.org/10.1016/j.coldregions.2010.01.005.

[8] B.P. Jelle, T. Gao, S.A. Mofid, T. Kolås, P.M. Stenstad, S. Ng, Avoiding snow and Ice formation on exterior solar cell surfaces - a review of research pathways and opportunities, in: Procedia Eng, 2016, pp. 699–706, https://doi.org/10.1016/j.proeng.2016.04.084.

[9] J. Chen, J. Liu, M. He, K. Li, D. Cui, Q. Zhang, X. Zeng, Y. Zhang, J. Wang, Y. Song, Superhydrophobic surfaces cannot reduce ice adhesion, Appl. Phys. Lett. 101 (2012) 111603, https://doi.org/10.1063/1.4752436.

[10] K.K. Varanasi, T. Deng, J.D. Smith, M. Hsu, N. Bhate, Frost formation and ice adhesion on superhydrophobic surfaces, Appl. Phys. Lett. 97 (2010) 234102, https://doi.org/10.1063/1.3524513.

[11] A.J. Meuler, J.D. Smith, K.K. Varanasi, J.M. Mabry, G.H. McKinley, R.E. Cohen, Relationships between water wettability and ice adhesion, ACS Appl. Mater. Interfaces 2 (2010) 3100–3110, https://doi.org/10.1021/am1006035.

[12] K. Golovin, S.P.R. Kobaku, D.H. Lee, E.T. DiLoreto, J.M. Mabry, A. Tuteja, Designing durable icephobic surfaces, Sci. Adv. 2 (2016), https://doi.org/10.1126/sciadv.1501496 e1501496–e1501496.

[13] P. Kim, T.S. Wong, J. Alvarenga, M.J. Kreder, W.E. Adorno-Martinez, J. Aizenberg, Liquid-infused nanostructured surfaces with extreme anti-ice and anti-frost performance, ACS Nano 6 (2012) 6569–6577, https://doi.org/10.1021/nn302310q.

[14] J. Chen, R. Dou, D. Cui, Q. Zhang, Y. Zhang, F. Xu, X. Zhou, J. Wang, Y. Song, L. Jiang, Robust prototypical anti-icing coatings with a self-lubricating liquid

water layer between ice and substrate, ACS Appl. Mater. Interfaces 5 (2013) 4026–4030, https://doi.org/10.1021/am401004t.

[15] P. Guo, Y. Zheng, M. Wen, C. Song, Y. Lin, L. Jiang, Icephobic/anti-icing properties of micro/nanostructured surfaces, Adv. Mater. 24 (2012) 2642–2648, https://doi.org/10.1002/adma.201104412.

[16] L. Cao, A.K. Jones, V.K. Sikka, J. Wu, D. Gao, Anti-icing superhydrophobic coatings, Langmuir 25 (2009) 12444–12448, https://doi.org/10.1021/la902882b.

[17] Q. Hao, Y. Pang, Y. Zhao, J. Zhang, J. Feng, S. Yao, Mechanism of delayed frost growth on superhydrophobic surfaces with jumping condensates: more than interdrop freezing, Langmuir 30 (2014) 15416–15422, https://doi.org/10.1021/la504166x.

[18] V. Hejazi, K. Sobolev, M. Nosonovsky, Supplementary Materials - from superhydrophobicity to icephobicity : force and interaction analysis, Sci. Rep. 3 (2013) 1–6. http://www.nature.com/srep/2013/130712/srep02194/extref/srep02194-s1.pdf.

[19] M.J. Kreder, J. Alvarenga, P. Kim, J. Aizenberg, Design of anti-icing surfaces: smooth, textured or slippery? Nat. Rev. Mater. 1 (2016) 15003, https://doi.org/10.1038/natrevmats.2015.3.

[20] P.O. Andersson, B.P. Jelle, Z. Zhang, Passive snow repulsion: a state-of-the-art review illuminating research gaps and possibilities, in: Energy Procedia, 2017, pp. 423–428, https://doi.org/10.1016/j.egypro.2017.09.650.

[21] M. He, J. Wang, H. Li, Y. Song, Super-hydrophobic surfaces to condensed micro-droplets at temperatures below the freezing point retard ice/frost formation, Soft Matter 7 (2011) 3993, https://doi.org/10.1039/c0sm01504k.

[22] P. Irajizad, M. Hasnain, N. Farokhnia, S.M. Sajadi, H. Ghasemi, Magnetic slippery extreme icephobic surfaces, Nat. Commun. 7 (2016) 13395, https://doi.org/10.1038/ncomms13395.

[23] T. Kako, A. Nakajima, H. Irie, Z. Kato, K. Uematsu, T. Watanabe, K. Hashimoto, Adhesion and sliding of wet snow on a super-hydrophobic surface with hydrophilic channels, J. Mater. Sci. 39 (2004) 547–555, https://doi.org/10.1023/B:JMSC.0000011510.92644.3f.

[24] K. Rykaczewski, S. Anand, S.B. Subramanyam, K.K. Varanasi, Cryo-FIB/SEM investigation of mechanism of frost formation on lubricant- impregnated surfaces, Microsc. Microanal. 19 (2013) 926–927.

[25] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the Köppen-Geiger climate classification updated, Meteorol. Z. 15 (2006) 259–263, https://doi.org/10.1127/0941-2948/2006/0130.

[26] A.J. Dietz, C. Wohner, C. Kuenzer, European snow cover characteristics between 2000 and 2011 derived from improved modis daily snow cover products, Remote Sens. 4 (2012) 2432–2454, https://doi.org/10.3390/rs4082432.

[27] J.A. Duffie, W.A. Beckman, W.M. Worek, Solar Engineering of Thermal Processes, second ed., third ed., John Wiley & Sons Inc., Hoboken, NJ, 1994 https://doi.org/10.1115/1.2930068.

[28] J. Major, D.M. Gray, D.H. Male, Handbook of Snow: Principles, Processes, Management and Use, The Blackburn Press, New Jersey, 1981, https://doi.org/10.2307/1550934.

[29] C. Magono, Meteorological classification of snow crystals, J. Jpn. Soc. Snow Ice 24 (1962) 33–37, https://doi.org/10.5331/seppyo.24.33.

[30] L. Makkonen, Models for the growth of rime, glaze, icicles and wet snow on structures, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 358 (2000) 2913–2939, https://doi.org/10.1098/rsta.2000.0690.

[31] T.M. Schutzius, S. Jung, T. Maitra, P. Eberle, C. Antonini, C. Stamatopoulos, D. Poulikakos, Physics of icing and rational design of surfaces with extraordinary icephobicity, Langmuir 31 (2015) 4807–4821, https://doi.org/10.1021/la502586a.

[32] M. Farzaneh, K. Savadjiev, Statistical analysis of field data for precipitation icing accretion on overhead power lines, IEEE Trans. Power Deliv. 20 (2005) 1080–1087, https://doi.org/10.1109/TPWRD.2004.838518.

[33] K. Savadjiev, M. Farzaneh, Modeling of icing and ice shedding on overhead power lines based on statistical analysis of meteorological data, IEEE Trans. Power Deliv. 19 (2004) 715–721, https://doi.org/10.1109/TPWRD.2003.822527.

[34] R.W. Gent, N.P. Dart, J.T. Cansdale, Aircraft icing, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 358 (2000) 2873–2911, https://doi.org/10.1098/rsta.2000.0689.

[35] F. Mosher, D. Schaum, C. Herbster, T. Guinn, Analysis of Causes of Icing Conditions Which Contributed to the Crash of Continental Flight, vol. 3407, 2010.

[36] A. Criscione, I.V. Roisman, S. Jakirlić, C. Tropea, Towards modelling of initial and final stages of supercooled water solidification, Int. J. Therm. Sci. 92 (2015) 150–161, https://doi.org/10.1038/ncomms1630.

[37] T. Maitra, M.K. Tiwari, C. Antonini, P. Schoch, S. Jung, P. Eberle, D. Poulikakos, On the nanoengineering of superhydrophobic and impalement resistant surface textures below the freezing temperature, Nano Lett. 14 (2014) 172–182, https://doi.org/10.1021/nl4037092.

[38] J. Lv, Y. Song, L. Jiang, J. Wang, Bio-inspired strategies for anti-icing, ACS Nano 8 (2014) 3152–3169, https://doi.org/10.1021/nn406522n.

[39] G. Poots, P.L.I. Skelton, Thermodynamic models of wet-snow accretion: axial growth and liquid water content on a fixed conductor, Int. J. Heat Fluid Flow 16 (1995) 43–49, https://doi.org/10.1016/0142-727X(94)00007-Y.

[40] L.E. Kollár, O. Olqma, M. Farzaneh, Natural wet-snow shedding from overhead cables, Cold Reg. Sci. Technol. 60 (2010) 40–50, https://doi.org/10.1016/j.coldregions.2009.07.005.

[41] H. Sojoudi, M. Wang, N.D. Boscher, G.H. McKinley, K.K. Gleason, Durable and scalable icephobic surfaces: similarities and distinctions from superhydrophobic surfaces, Soft Matter 12 (2016) 1938–1963, https://doi.org/10.1039/C5SM02295A.

[42] W. Ambach, A. Denoth, On the dielectric constant of wet snow, Snow Mech. 114 (1975) 136–142. http://ks360352.kimsufi.com/redbooks/a114/iahs_114_0136.pdf. accessed April 10, 2018.

[43] W.I. Linlor, Permittivity and attenuation of wet snow between 4 and 12 GHz, J. Appl. Phys. 51 (1980) 2811–2816, https://doi.org/10.1063/1.327947.

[44] A.E. Walker, B.E. Goodison, Discrimination of a wet snow cover using passive microwave satellite data, Ann. Glaciol. 17 (1993) 307–311, https://doi.org/10.1017/S026030550001301X.

[45] B. Na, R.L. Webb, A fundamental understanding of factors affecting frost nucleation, Int. J. Heat Mass Transf. 46 (2003) 3797–3808, https://doi.org/10.1016/S0017-9310(03)00194-7.

[46] A. Weiss, H. Weiss, Photovoltaic cell electrical heating system for removing snow on panel including verification, in: Environ. Sci. Pollut. Res, IEEE, 2018, pp. 24561–24568, https://doi.org/10.1007/s11356-017-0251-4.

[47] A. Rahmatmand, S.J. Harrison, P.H. Oosthuizen, An experimental investigation of snow removal from photovoltaic solar panels by electrical heating, Sol. Energy 171 (2018) 811–826, https://doi.org/10.1016/j.solener.2018.07.015.

[48] R.M. Fillion, A.R. Riahi, A. Edrisy, A review of icing prevention in photovoltaic devices by surface engineering, Renew. Sustain. Energy Rev. 32 (2014) 797–809, https://doi.org/10.1016/j.rser.2014.01.015.

[49] R.A. Synowicki, B.D. Johs, A.C. Martin, Optical properties of soda-lime float glass from spectroscopic ellipsometry, Thin Solid Films 519 (2011) 2907–2913, https://doi.org/10.1016/j.tsf.2010.12.110.

[50] P. Heinstein, C. Ballif, L.E. Perret-Aebi, Building integrated photovoltaics (BIPV): review, potentials, barriers and myths, Green 3 (2013) 125–156, https://doi.org/10.1515/green-2013-0020.

[51] Z. He, Y. Zhuo, J. He, Z. Zhang, Design and preparation of sandwich-like polydimethylsiloxane (PDMS) sponges with super-low ice adhesion, Soft Matter 14 (2018) 4846–4851, https://doi.org/10.1039/c8sm00820e.

[52] Z.A. Janjua, B. Turnbull, K.L. Choy, C. Pandis, J. Liu, X. Hou, K.S. Choi, Performance and durability tests of smart icephobic coatings to reduce ice adhesion, Appl. Surf. Sci. 407 (2017) 555–564, https://doi.org/10.1016/j.apsusc.2017.02.206.

[53] B. Marion, R. Schaefer, H. Caine, G. Sanchez, Measured and modeled photovoltaic system energy losses from snow for Colorado and Wisconsin locations, Sol. Energy 97 (2013) 112–121, https://doi.org/10.1016/j.solener.2013.07.029.

[54] R.W. Andrews, J.M. Pearce, Prediction of energy effects on photovoltaic systems due to snowfall events, in: Conf. Rec. IEEE Photovolt. Spec. Conf, IEEE, 2012, pp. 3386–3391, https://doi.org/10.1109/PVSC.2012.6318297.

[55] A.S. GETEK Energy, BIPV for Norway, 2019. http://bipvno.no/. (Accessed 19 August 2019).

[56] R. Dou, J. Chen, Y. Zhang, X. Wang, D. Cui, Y. Song, L. Jiang, J. Wang, Anti-icing coating with an aqueous lubricating layer, ACS Appl. Mater. Interfaces 6 (2014) 6998–7003, https://doi.org/10.1021/am501252u.

[57] C. Stamatopoulos, J. Hemrle, D. Wang, D. Poulikakos, Exceptional anti-icing performance of self-impregnating slippery surfaces, ACS Appl. Mater. Interfaces 9 (2017) 10233–10242, https://doi.org/10.1021/acsami.7b00186.

[58] S. Chernyy, M. Järn, K. Shimizu, A. Swerin, S.U. Pedersen, K. Daasbjerg, L. Makkonen, P. Claesson, J. Iruthayaraj, Superhydrophilic polyelectrolyte brush layers with imparted anti-icing properties: effect of counter ions, ACS Appl. Mater. Interfaces 6 (2014) 6487–6496, https://doi.org/10.1021/am500046d.

[59] R.N. Wenzel, Resistance of solid surfaces to wetting by water, Ind. Eng. Chem. 28 (1936) 988–994, https://doi.org/10.1021/ie50320a024.

[60] A.B.D. Cassie, S. Baxter, Wettability of porous surfaces, Trans. Faraday Soc. 40 (1944) 546, https://doi.org/10.1039/tf9444000546.

[61] L. Feng, Y. Zhang, J. Xi, Y. Zhu, N. Wang, F. Xia, L. Jiang, Petal effect: a superhydrophobic state with high adhesive force, Langmuir 24 (2008) 4114–4119, https://doi.org/10.1021/la703821h.

[62] A. Criscione, I.V. Roisman, S. Jakirlić, C. Tropea, Towards modelling of initial and final stages of supercooled water solidification, Int. J. Therm. Sci. 92 (2015) 150–161, https://doi.org/10.1038/ncomms1630.

[63] Y. Shen, J. Tao, H. Tao, S. Chen, L. Pan, T. Wang, Anti-icing potential of superhydrophobic Ti6Al4V surfaces: ice nucleation and growth, Langmuir 31 (2015) 10799–10806, https://doi.org/10.1021/acs.langmuir.5b02946.

[64] B. Liu, K. Zhang, C. Tao, Y. Zhao, X. Li, K. Zhu, X. Yuan, Strategies for anti-icing: low surface energy or liquid-infused? RSC Adv. 6 (2016) 70251–70260, https://doi.org/10.1039/c6ra11383d.

[65] B. Balu, V. Breedveld, D.W. Hess, Fabrication of "roll-off" and "sticky" superhydrophobic cellulose surfaces-via plasma processing, Langmuir 24 (2008) 4785–4790, https://doi.org/10.1021/la703766c.

[66] S. Dash, M.T. Alt, S.V. Garimella, Hybrid surface design for robust superhydrophobicity, Langmuir 28 (2012) 9606–9615, https://doi.org/10.1021/la301743p.

[67] P. Tsai, S. Pacheco, C. Pirat, L. Lefferts, D. Lohse, Drop impact upon micro- and nanostructured superhydrophobic surfaces, Langmuir 25 (2009) 12293–12298, https://doi.org/10.1021/la900330q.

[68] J.O. Laws, Measurements of the fall velocities of waterdrops and raindrops, Trans. Geophys. Union 22 (1941) 709–721.

[69] J.H. Kim, J.P. Rothstein, Droplet impact dynamics on lubricant-infused superhydrophobic surfaces: the role of viscosity ratio, Langmuir 32 (2016) 10166–10176, https://doi.org/10.1021/acs.langmuir.6b01994.

[70] S. Jung, M. Dorrestijn, D. Raps, A. Das, C.M. Megaridis, D. Poulikakos, Are superhydrophobic surfaces best for icephobicity? Langmuir 27 (2011) 3059–3066, https://doi.org/10.1021/la104762g.

[71] P. Hao, C. Lv, X. Zhang, Freezing of sessile water droplets on surfaces with various roughness and wettability, Appl. Phys. Lett. 104 (2014) 161609, https://doi.org/10.1063/1.4873345.

[72] D.P. Singh, J.P. Singh, Delayed freezing of water droplet on silver nanocolumnar thin film, Appl. Phys. Lett. 102 (2013) 243112, https://doi.org/10.1063/1.4811751.

[73] G. Graeber, T.M. Schutzius, H. Eghlidi, D. Poulikakos, Spontaneous self-dislodging of freezing water droplets and the role of wettability, Proc. Natl. Acad. Sci. 114 (2017) 11040–11045, https://doi.org/10.1073/pnas.1705952114.

[74] L. Oberli, D. Caruso, C. Hall, M. Fabretto, P.J. Murphy, D. Evans, Condensation and freezing of droplets on superhydrophobic surfaces, Adv. Colloid Interface Sci. 210 (2014) 47–57, https://doi.org/10.1016/j.cis.2013.10.018.

[75] T.M. Schutzius, S. Jung, T. Maitra, G. Graeber, M. Köhme, D. Poulikakos, Spontaneous droplet trampolining on rigid superhydrophobic surfaces, Nature 527 (2015) 82–85, https://doi.org/10.1038/nature15738.

[76] R. DeHoff, Thermodynamics in Materials Science, CRC Press, 2006, https://doi.org/10.15713/ins.mmj.3.

[77] C. Antonini, M. Innocenti, T. Horn, M. Marengo, A. Amirfazli, Understanding the effect of superhydrophobic coatings on energy reduction in anti-icing systems, Cold Reg. Sci. Technol. 67 (2011) 58–67, https://doi.org/10.1016/j.coldregions.2011.02.006.

[78] K.K. Varanasi, M. Hsu, N. Bhate, W. Yang, T. Deng, Spatial control in the heterogeneous nucleation of water, Appl. Phys. Lett. 95 (2009) 133109, https://doi.org/10.1063/1.3200951.

[79] G.P. Johari, The Gibbs-Thomson effect and intergranular melting in ice emulsions: interpreting the anomalous heat capacity and volume of supercooled water, J. Chem. Phys. 107 (1997) 10154–10165, https://doi.org/10.1063/1.475322.

[80] J.B. Boreyko, R.R. Hansen, K.R. Murphy, S. Nath, S.T. Retterer, C.P. Collier, Controlling condensation and frost growth with chemical micropatterns, Sci. Rep. 6 (2016) 19131, https://doi.org/10.1038/srep19131.

[81] Y. Liu, L. Ma, W. Wang, A.K. Kota, H. Hu, An experimental study on soft PDMS materials for aircraft icing mitigation, Appl. Surf. Sci. 447 (2018) 599–609, https://doi.org/10.1016/j.apsusc.2018.04.032.

[82] A.G. Kraj, E.L. Bibeau, Measurement method and results of ice adhesion force on the curved surface of a wind turbine blade, Renew. Energy 35 (2010) 741–746, https://doi.org/10.1016/j.renene.2009.08.030.

[83] R. Karmouch, G.G. Ross, Superhydrophobic wind turbine blade surfaces obtained by a simple deposition of silica nanoparticles embedded in epoxy, Appl. Surf. Sci. 257 (2010) 665–669, https://doi.org/10.1016/j.apsusc.2010.07.041.

[84] M.A. Sarshar, C. Swarctz, S. Hunter, J. Simpson, C.H. Choi, Effects of contact angle hysteresis on ice adhesion and growth on superhydrophobic surfaces under dynamic flow conditions, Colloid Polym. Sci. 291 (2013) 427–435, https://doi.org/10.1007/s00396-012-2753-4.

[85] S.A. Kulinich, M. Farzaneh, How wetting hysteresis influences ice adhesion strength on superhydrophobic surfaces, J. Adhes. Sci. Technol. 25 (2009) 4056–4060, https://doi.org/10.1021/la901439c.

[86] M. Nosonovsky, V. Hejazi, Why superhydrophobic surfaces are not always icephobic, ACS Nano 6 (2012) 8488–8491, https://doi.org/10.1021/nn302138r.

[87] Z. He, E.T. Vågenes, C. Delabahan, J. He, Z. Zhang, Room temperature characteristics of polymer-based low ice adhesion surfaces, Sci. Rep. 7 (2017), https://doi.org/10.1038/srep42181.

[88] S.A. Kulinich, M. Farzaneh, Ice adhesion on super-hydrophobic surfaces, Appl. Surf. Sci. 255 (2009) 8153–8157, https://doi.org/10.1016/j.apsusc.2009.05.033.

[89] Z. He, S. Xiao, H. Gao, J. He, Z. Zhang, Multiscale crack initiator promoted super-low ice adhesion surfaces, Soft Matter 13 (2017) 6562–6568, https://doi.org/10.1039/c7sm01511a.

[90] P. Zhang, F.Y. Lv, A review of the recent advances in superhydrophobic surfaces and the emerging energy-related applications, Energy 82 (2015) 1068–1087, https://doi.org/10.1016/j.energy.2015.01.061.

[91] R. Ramachandran, M. Kozhukhova, K. Sobolev, M. Nosonovsky, Anti-icing superhydrophobic surfaces: controlling entropic molecular interactions to design novel icephobic concrete, Entropy 18 (2016), https://doi.org/10.3390/e18040132.

[92] N. Wang, D. Xiong, Y. Deng, Y. Shi, K. Wang, Mechanically robust superhydrophobic steel surface with anti-icing, UV-durability, and corrosion resistance properties, ACS Appl. Mater. Interfaces 7 (2015) 6260–6272, https://doi.org/10.1021/acsami.5b00558.

[93] K. Rykaczewski, S. Anand, S.B. Subramanyam, K.K. Varanasi, Mechanism of frost formation on lubricant-impregnated surfaces, Langmuir 29 (2013) 5230–5238, https://doi.org/10.1021/la400801s.

[94] M. Zou, S. Beckford, R. Wei, C. Ellis, G. Hatton, M.A. Miller, Effects of surface roughness and energy on ice adhesion strength, Appl. Surf. Sci. 257 (2011) 3786–3792, https://doi.org/10.1016/j.apsusc.2010.11.149.

[95] G. Fortin, J. Perron, Ice adhesion models to predict shear stress at shedding, J. Adhes. Sci. Technol. 26 (2012) 523–553, https://doi.org/10.1163/016942411X574835.

[96] K. Golovin, A. Dhyani, M.D. Thouless, A. Tuteja, Low-interfacial Toughness Materials for Effective Large-Scale Deicing, 2019, https://doi.org/10.1126/science.aav1266.

[97] S.B. Subramanyam, K. Rykaczewski, K.K. Varanasi, Ice Adhesion on Lubricant-Impregnated Textured Surfaces, 2013, https://doi.org/10.1021/la402456c.

[98] V.F. Petrenko, The effect of static electric fields on ice friction, J. Appl. Phys. 76 (1994) 1216–1219, https://doi.org/10.1063/1.357850.

[99] I.A. Ryzhkin, V.F. Petrenko, Physical mechanisms responsible for ice adhesion, J. Phys. Chem. B 101 (1997) 6267–6270, https://doi.org/10.1021/jp9632145.

[100] C.J. Van Oss, R.J. Good, M.K. Chaudhury, The role of van der Waals forces and hydrogen bonds in "hydrophobic interactions" between biopolymers and low energy surfaces, J. Colloid Interface Sci. 111 (1986) 378–390, https://doi.org/10.1016/0021-9797(86)90041-X.

[101] M.P. Goertz, X.Y. Zhu, J.E. Houston, Exploring the liquid-like layer on the ice surface, Langmuir 25 (2009) 6905–6908, https://doi.org/10.1021/la9001994.

[102] A. Döppenschmidt, H.J. Butt, Measuring the thickness of the liquid-like layer on ice surfaces with atomic force microscopy, Langmuir 16 (2000) 6709–6714, https://doi.org/10.1021/la990799w.

[103] N. Saleema, M. Farzaneh, R.W. Paynter, D.K. Sarkar, Prevention of ice accretion on aluminum surfaces by enhancing their hydrophobic properties, J. Adhes. Sci. Technol. 25 (2011) 27–40, https://doi.org/10.1163/016942410X508064.

[104] A. Work, Y. Lian, A critical review of the measurement of ice adhesion to solid substrates, Prog. Aerosp. Sci. 98 (2018) 1–26, https://doi.org/10.1016/j.paerosci.2018.03.001.

[105] T. Bharathidasan, S.V. Kumar, M.S. Bobji, R.P.S. Chakradhar, B.J. Basu, Effect of wettability and surface roughness on ice-adhesion strength of hydrophilic, hydrophobic and superhydrophobic surfaces, Appl. Surf. Sci. 314 (2014) 241–250, https://doi.org/10.1016/j.apsusc.2014.06.101.

[106] M.R. Kasaai, M. Farzaneh, A critical review of evaluation methods of ice adhesion strength on the surface of materials, in: 23rd Int. Conf. Offshore Mech. Arct. Eng, vol. 3, ASME, 2004, pp. 919–926, https://doi.org/10.1115/OMAE2004-51264.

[107] M. Schulz, M. Sinapius, Evaluation of different ice adhesion tests for mechanical deicing systems, in: SAE Tech. Pap, 2015, https://doi.org/10.4271/2015-01-2135.

[108] S. Rønneberg, C. Laforte, C. Volat, J. He, Z. Zhang, The effect of ice type on ice adhesion, AIP Adv. 9 (2019), https://doi.org/10.1063/1.5086242.

[109] L. Makkonen, B. Wichura, Simulating wet snow loads on power line cables by a simple model, Cold Reg. Sci. Technol. 61 (2010) 73–81, https://doi.org/10.1016/j.coldregions.2010.01.008.

[110] Y. Sakamoto, Snow accretion on overhead wires, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 358 (2000) 2941–2970, https://doi.org/10.1098/rsta.2000.0691.

[111] R.W. Andrews, A. Pollard, J.M. Pearce, A new method to determine the effects of hydrodynamic surface coatings on the snow shedding effectiveness of solar photovoltaic modules, Sol. Energy Mater. Sol. Cells 113 (2013) 71–78, https://doi.org/10.1016/j.solmat.2013.01.032.

[112] J.J. Petrovic, Mechanical Properties of Ice and Snow, 2003, https://doi.org/10.1023/A:1021134128038.

[113] H. Saito, K.I. Takai, H. Takazawa, G. Yamauchi, A study on snow sticking weight to water-repellent coatings, Mater. Sci. Res. Int. 3 (1997) 216–219, https://doi.org/10.2472/jsms.46.12appendix_216.

[114] Y. Furukawa, J.S. Wettlaufer, Snow and ice crystals, Phys. Today 60 (2007) 70–71, https://doi.org/10.1063/1.2825081.

[115] K.G. Libbrecht, The physics of snow crystals, Rep. Prog. Phys. 68 (2005) 855–895, https://doi.org/10.1088/0034-4885/68/4/R03.

[116] S.R. Corsi, S.W. Geis, J.E. Loyo-Rosales, C.P. Rice, R.J. Sheesley, G.G. Failey, D. A. Cancilla, Characterization of aircraft deicer and anti-icer components and toxicity in airport snowbanks and snowmelt runoff, Environ. Sci. Technol. 40 (2006) 3195–3202, https://doi.org/10.1021/es052028m.

[117] P. O'Brien, Reducing the cost and environmental impact of aircraft de-icing. AIAA's 3rd Annu. Aviat. Technol. Integr. Oper. Forum, American Institute of Aeronautics and Astronautics, Reston, Virigina, 2012, https://doi.org/10.2514/6.2003-6773.

[118] A. Omazic, G. Oreski, M. Halwachs, G.C. Eder, C. Hirschl, L. Neumaier, G. Pinter, M. Erceg, Relation between degradation of polymeric components in crystalline silicon PV module and climatic conditions: a literature review, Sol. Energy Mater. Sol. Cells 192 (2019) 123–133, https://doi.org/10.1016/j.solmat.2018.12.027.

[119] B.B. Aarseth, M.B. Øgaard, J. Zhu, T. Strömberg, J.A. Tsanakas, J.H. Selj, E. S. Marstein, Mitigating Snow on Rooftop PV Systems for Higher Energy Yield and Safer Roofs, 2018, https://doi.org/10.4229/35thEUPVSEC2018-6CO.3.5.

[120] T. Wang, Y. Zheng, A.R.O. Raji, Y. Li, W.K.A. Sikkema, J.M. Tour, Passive anti-icing and active deicing films, ACS Appl. Mater. Interfaces 8 (2016) 14169–14173, https://doi.org/10.1021/acsami.6b03060.

[121] J. Palacios, E. Smith, J. Rose, R. Royer, Instantaneous de-icing of freezer ice via ultrasonic actuation, AIAA J. 49 (2011) 1158–1167, https://doi.org/10.2514/1.J050143.

[122] Z. Wang, Recent progress on ultrasonic de-icing technique used for wind power generation, high-voltage transmission line and aircraft, Energy Build. 140 (2017) 42–49, https://doi.org/10.1016/j.enbuild.2017.01.072.

[123] M. Adochitei, C. Harabagiu, D. Astanei, R. Burlica, A new solar energy converting system with vertical photovoltaic panels, in: 2014 Int. Conf. Expo. Electr. Power Eng., IEEE, a: pp. 1129–1131. doi:10.1109/ICEPE.2014.6970085.

[124] A. Gheitasi, A. Almaliky, N. Albaqawi, Development of an automatic cleaning system for photovoltaic plants, in: 2015 IEEE PES Asia-Pacific Power Energy Eng. Conf, IEEE, 2015, pp. 1–4, https://doi.org/10.1109/APPEEC.2015.7380938.

[125] A.A. Kazem, M.T. Chaichan, H.A. Kazem, Dust effect on photovoltaic utilization in Iraq: review article, Renew. Sustain. Energy Rev. 37 (2014) 734–749, https://doi.org/10.1016/j.rser.2014.05.073.

[126] R.E. Pawluk, Y. Chen, Y. She, Photovoltaic electricity generation loss due to snow – a literature review on influence factors, estimation, and mitigation, Renew. Sustain. Energy Rev. 107 (2019) 171–182, https://doi.org/10.1016/j.rser.2018.12.031.

[127] L. Powers, J. Newmiller, T. Townsend, Measuring and modeling the effect of snow on photovoltaic system performance, in: Conf. Rec. IEEE Photovolt. Spec. Conf, IEEE, 2010, pp. 973–978, https://doi.org/10.1109/PVSC.2010.5614572.

[128] A.A. Amr, A.A.M. Hassan, M. Abdel-Salam, A.M. El-Sayed, Enhancement of photovoltaic system performance via passive cooling: theory versus experiment, Renew. Energy 140 (2019) 88–103, https://doi.org/10.1016/j.renene.2019.03.048.
[129] R.W. Andrews, J.M. Pearce, The effect of spectral albedo on amorphous silicon and crystalline silicon solar photovoltaic device performance, Sol. Energy 91 (2013) 233–241, https://doi.org/10.1016/j.solener.2013.01.030.
[130] A. Kosonen, J. Ahola, C. Breyer, A. Albo, Large scale solar power plant in Nordic conditions, in: 2014 16th Eur. Conf. Power Electron. Appl. EPE-ECCE Eur. 2014, IEEE, 2014, pp. 1–10, https://doi.org/10.1109/EPE.2014.6911030.
[131] A.-N. Azmi, M.L. Kohle, A.G. Imenes, On-grid residential development with photovoltaic systems in Southern Norway, in: 2013 IEEE Conf. Clean Energy Technol, IEEE, 2013, pp. 93–97, https://doi.org/10.1109/CEAT.2013.6775606.
[132] T. Aytug, A.R. Lupini, G.E. Jellison, P.C. Joshi, I.H. Ivanov, T. Liu, P. Wang, R. Menon, R.M. Trejo, E. Lara-Curzio, S.R. Hunter, J.T. Simpson, M. P. Paranthaman, D.K. Christen, Monolithic graded-refractive-index glass-based antireflective coatings: broadband/omnidirectional light harvesting and self-cleaning characteristics, J. Mater. Chem. C. 3 (2015) 5440–5449, https://doi.org/10.1039/c5tc00499c.
[133] X. Zhang, Y. Guo, Z. Zhang, P. Zhang, Self-cleaning superhydrophobic surface based on titanium dioxide nanowires combined with polydimethylsiloxane, Appl. Surf. Sci. 284 (2013) 319–323, https://doi.org/10.1016/j.apsusc.2013.07.100.
[134] C. Klinger, O. Landeg, V. Murray, Power outages, extreme events and health: a systematic review of the literature from 2011-2012, PLoS Curr. 6 (2014), https://doi.org/10.1371/currents.dis.04eb1dc5e73dd1377e05a10e9edde673.
[135] C.E. Colten, R.W. Kates, S.B. Laska, Three years after Katrina: lessons for community resilience, Environment 50 (2008) 36–47, https://doi.org/10.3200/ENVT.50.5.36-47.
[136] Norwegian Directorate for Civil Protection, National Risk Analysis 2014, Tønsberg, 2014. https://www.dsb.no/globalassets/dokumenter/rapporter/nrb_2014_english.pdf. (Accessed 18 July 2019).
[137] J. He, Y. Pan, B. Liang, C. Wang, A simple decentralized islanding microgrid power sharing method without using droop control, IEEE Trans. Smart Grid 9 (2018) 6128–6139, https://doi.org/10.1109/TSG.2017.2703978.
[138] V.F. Petrenko, I.A. Ryzhkin, Surface States of Charge Carriers and Electrical Properties of the Surface Layer of Ice, 1997, https://doi.org/10.1021/jp963216p.

Article III

A Gravity-based Method for Measuring Snow Adhesion

III

Per-Olof A. Borrebæk, Bjørn Petter Jelle, Alex Klein-Paste, Zhiliang Zhang, Josefine Selj, Erik Stensrud Marstein

(*Submitted for publication*)

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Article IV

Snow adhesion on icephobic surfaces

Per-Olof A. Borrebæk, Sigrid Rønneberg, Tong Li, Bjørn Petter Jelle, Alex Klein-Paste, Zhiliang Zhang

IV

(*Submitted for publication*)

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Article V

Influence of glass surface roughness in the microstructure range on snow adhesion

Per-Olof A. Borrebæk, Bjørn Petter Jelle, Alex Klein-Paste, Zhiliang Zhang

(*Submitted for publication*)

V

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Article VI

A framework for classification of snow- and icephobicity

Per-Olof A. Borrebæk, Sigrid Rønneberg, Bjørn Petter Jelle, Alex Klein-Paste, Zhiliang Zhang, Jianying He

(*Submitted for publication*)

VI

A framework for classification of snow- and icephobicity

Per-Olof A. Borrebæk[a], Sigrid Rønneberg[c], Bjørn Petter Jelle[ab], Alex Klein-Paste[a], Zhiliang Zhang[c], Jianying He[c]

[a] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway

[b] Department of Materials and Structures, SINTEF Community, NO-7465 Trondheim, Norway

[c] Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway

Abstract

For decades, there has been no proper thermodynamic definition of icephobicity. Some claim icephobic properties at an adhesion lower than 100 kPa, whereas others claim it when the accretion of ice is significantly prolonged. Herein we propose to use a terminology based on the type of precipitation and physical behaviour, separating ice and snow in adhesion and accretion. This is done in order to lay a foundation on which to introduce a framework for classification of snow- and icephobic surfaces. Such a classification empowers users and producers of such surfaces to communicate accurately about performances and expectations of surfaces and coatings. We include snowphobicity in this scheme, as snow is closely related to the traditional icephobicity and often exhibit overlapping requirements.

Keywords: Adhesion; accretion; ice; snow; definition; crynerophobic, icephobic, snowphobic, surface

1 Introduction

Snow and ice accumulation on various surfaces are a wide-spread problem in the cold regions of the world with a large financial impact on a wide variety of societal functions. Aircraft [1], airborne powerlines [2], wind power turbine blades [3], and photovoltaic panels [4] are all familiar examples. The high cost of maintaining some of these systems has induced significant investments in research focused on mitigation of the problems of snow and ice accumulation. One of the greatest driving forces has been the aeronautics industry where icing can have lethal consequences [5].

Icephobicity has been defined differently by different researchers. Some note icephobicity as low ice adhesion, often defined by the limit 100 kPa [6], whereas others note icephobicity as a significant delay of ice accretion [7]. This difference is sometimes referred to as *de-icing* vs. *anti-icing* surfaces. Assuming icephobicity is thought of as both, the definition has two weaknesses: (i) It conflates ice adhesion and ice accretion, thus confusing the communication of requirements, results, and expectations. (ii) The given limit of adhesion may apply to the aeronautics industry, but simultaneously has no bearing on other implementations. In addition, there is a seemingly common terminological conflation of the mitigation of *ice adhesion*, *ice accretion* and *snow adhesion* [8]. While related, ice adhesion and snow adhesion have been shown to behave quite differently from an engineering perspective [9].

Frost accretion is also a relevant aspect to consider. As shown by Varanasi et al. [10], surfaces may be designed to be superhydrophobic but lose their intended low ice adhesion if frost accretion occurs. Therefore, frost accretion is here viewed as a type of ice accretion. There are thus three paths for ice accretion: freezing of impacting water droplets, freezing of droplets condensing on a surface, or desublimation of water vapour into ice.

The success or failure of a surface in mitigating these three facets (ice adhesion, ice accretion, and snow adhesion) must be viewed from the perspective of the targeted application. To address this matter, we here suggest a new way of presenting the adhesion and accretion mitigating effect of snow and ice of a surface, through a classification system. We shall not provide a full classification protocol with procedures, but rather limit ourselves to suggesting and discussing a system framework on which to build such a classification system. In doing so, the shaping and refining of the system can become a collaborative effort within the field.

2 Proposition

2.1 Separation of terms

Firstly, we must properly disjoin the adhesion and accretion of ice from the classical icephobicity, in order to counter the first weakness mentioned above. Adhesion, we here define in the traditional manner, as the shear force per interfacial area required to dislodge a stationary ice sample, regardless of how it was formed. This definition is in accordance with the most common ice adhesion test methods which utilize shear force to detach the ice [11]. Accretion we define as the time-delay before ice (or frost) begins to accrete, at some standard conditions. This follows from the common manner of determining anti-icing [7,12]

As snow cannot be prevented from forming in the atmosphere, it must either be prevented from interacting with the surface or the adhesion strength of the snow must be minimized. Thus, snowphobicity will here be defined to consist only of the adhesion aspect. Though both ice and snow are intrinsically frozen water, their formation and interaction with surfaces are different enough that they warrant separate definitions, as seen in a recent study [9].

2.2 Classification syntax

In the field of electronics, there is an established classification for moisture and dust protection called ingress protection code [13]. This is a common and easy-to-grasp system for people who work with electronics to define requirements and to know what products fulfil said requirements. The syntax consists of a descriptor, *IP*, followed by two integer numbers: One representing the dust repulsion grade and one representing the water tightness grade. A similar concept is here introduced for the classification of cold precipitation mitigation, including adhesion of accretion of both snow and ice.

The three main facets of cold precipitation isolated previously, may be gathered under the common umbrella term *crynerophobic* (Greek: cryo = cold, nero = water, phobos = fear), implying the point at which all three facets overlap as schematically shown in figure 1. For the present purposes, this term may be applied as a descriptor, easily abbreviated *CNP*. This descriptor must then be followed by three integer numbers representing the degree of ice adhesion mitigation, ice accretion delay, and snow adhesion mitigation.

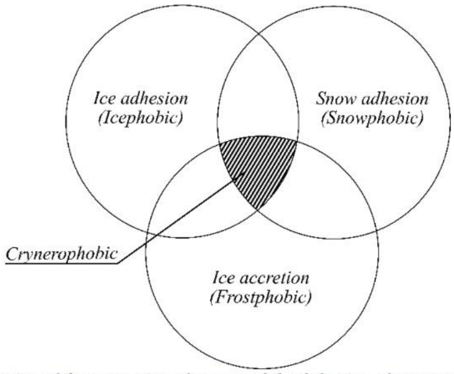

Figure 1: Graphical representation of the separation of terms and the definition of crynerophobicity. Terms are defined in the negative, i.e. the aspect to be mitigated or delayed, with a term in the positive form in parenthesis.

Ice, however, comes in many forms and with different adhesive behaviours, as recently pointed out by Rønneberg et al. [14], and the same most likely applies to snow. This variation creates a potential divide in classification strategy where one might either opt for a standardized type of ice and snow to which other types might be correlated, or one might specify the type of ice and snow used for the specific standard. These two strategies will here be visited in some more detail.

2.2.1 Syntax alternatives

By using a standardized ice type, the syntax becomes more easily recognized and read, as it applies to all cases. A mock-up of such a syntax is shown in figure 2. In order to properly implement this syntax, however, all types of ice and snow have to be accurately related in a manner currently not available. Such correlations will require accurate modelling which in turn requires a comprehensive repository of data. Data must be collected from measurements of various ice and snow types as well as the methods used to acquire them, under all manner of conditions.

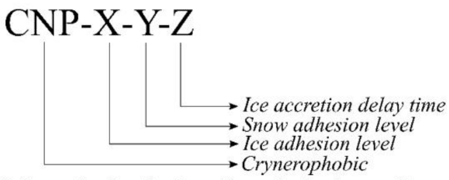

Figure 2: Syntax for classification with standardized types of ice and snow.

As such a repository is currently not compiled and models for correlation does not presently exist, an alternative approach may be to specify ice and snow types. Such data can be more readily found in the literature and is thus more readily implementable in a classification system. The syntax could be implemented as seen in figure 3, where the ice type, *i*, is specified for the ice adhesion level, the snow type, *j*, for the snow adhesion level, and ice accretion path, *k*, for the accretion delay. Using this approach, however, the classification will apply only to the specified type of ice and snow combination. It may not be transferable between different types of precipitation, and if a surface or coating is developed for several applications, it needs to be tested for all relevant types of precipitation. Though a sharp division between ice and snow types is rarely the case in nature, where environmental conditions change rapidly and present more as a continuum, one may qualitatively interpolate to estimate the impact of such a snow and/or ice continuum.

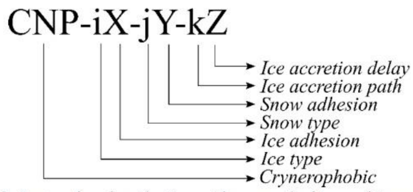

Figure 3: Syntax for classifcation with a specified type of ice and snow.

Incorporation of more widely applicable specifications, e.g. a range of ice and snow types, will then require the use of a list of classifications for ice and snow. For ice, such precipitation types could be based on the ice types described in the ISO standard for atmospheric icing on structures, ISO 12494:2017. It defines the ice types *glaze ice*, *hard rime*, *soft rime and wet snow*. To this range, it appears prudent to add *bulk water ice* (sessile bulk water frozen onto substrate), as it may differ from glaze ice [14].

As discussed, snow should be treated separately, and hence wet snow should be excepted from the ice types. Instead, it should be incorporated in a range of snow types, separated on the basis of being pre-frozen (prior to surface contact) precipitation. Snow types should include the classical separation of *dry snow* and *wet snow*, as well as *hail* and *graupel*.

Ice has three major pathways for accretion. Airborne condensed water droplets that impact the surface, here discussed as *impact icing*, freezing of droplets condensing on the surface, here called *condensation frosting*, and *desublimation frosting* where water vapour deposits as solid ice without condensation of liquid water. Impact icing will, as here defined, result in glaze ice or rime if allowed to accrete.

More types could be included in the future if found useful. A list of the discussed types may be seen in table 1, with a corresponding illustration in figure 4. We have here suggested Greek lettering for these variables, so as to logically separate them from the other elements.

Table 1: Overview of suggested ice and snow type ranges.

Type	i	j	k
α	Bulk Water Ice	Wet Snow	Impact icing
β	Glaze Ice	Dry Snow	Condensation frosting
γ	Hard Rime	Graupel	Desublimation frosting
δ	Soft Rime	Hail	

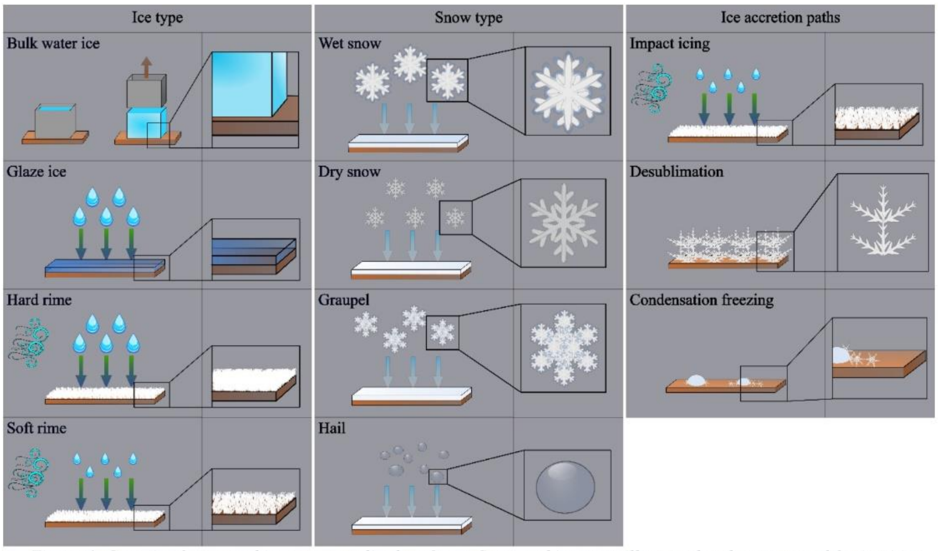

Figure 4: Genesis of snow and ice on generalized surfaces: Snow and ice types illustrated and exaggerated for intuitive understanding of unique features. Each type shows both process of formation and a detailed excerpt, where it should be noted that the formation of hard and soft rime occurs through a process of freezing rain/drizzle, often in strong wind.

2.2.2 *Interpretation*

In order to dissuade confusion, the numbers representing the three core facets of cold precipitation can either be interpreted as "higher is better" or "lower is better". Ether choice will provide the same useful information but may create confusion if all numbers do not adhere to the same interpretation scheme. Therefore, it may be most beneficial if increasing the number for adhesion constrict adhesion levels and the inverse holds true for accretion, or vice versa. E.g. a higher number for adhesion indicates a lower adhesion level and a higher number for accretion indicates a lower level of adhesion. That way *CNP-α9-β9-γ9* would indicate the best of all crynerophobicity facets for bulk water ice and dry snow. By similarity to what is familiar from e.g. the ingress protection code, there is an argument for the "higher is better" scheme being more intuitive.

2.2.3 *Ranges and limits*

The integer numbers used to indicate the levels adhesion and accretion should range 1-9 with the possible addition of 0. Exceeding single digits, however, incurs the risk of miscommunication as there is then no obvious upper limit, i.e. does it go to 9, 99, or does it go on forever? Similarly, the use of 0 could be misunderstood as an absence of mitigation. Assuming a range from 1-9, each level must then reflect a measurable level of adhesion or accretion.

As a first approach, we propose a simple linear scaling for each if the variables and quantify the upper and lower bounds based on some of the most well cited publications. An overview can be seen in table 2. For ice adhesion, the lower bound ($X = 1$) is set to 100 kPa as it has often been cited as a limit for icephobicity [6,15,16], and the upper bound ($X = 9$) is set to 1 kPa as it has been one of the lowest published limits and may allow for spontaneous shedding [15,17]. It is also uncertain whether a further reduction in ice adhesion strength below this point is required for the purposes of ice shedding in realistic environments and for industry purposes. For snow adhesion, data is more scarce but an upper and lower bound have been set based on some recent results [9].

Ice accretion delay is logically reported as the time that ice accretion can be supressed. This is often tested by freezing time of a sessile droplet [7,18], though this would likely not be representative for all accretion pathways. In such cases one might determine a standard mass of ice, e.g. 1 g, that is to set the time of accretion. Such an approach has been utilized previously [19], though, not always in a standardized quantitative manner required for the present purposes [20]. For tentative range determination, we have used the scale used by Wang et al. [19] and extrapolated in a linear manner up to 300 minutes (5h).

*Table 2: First-approach suggestion for varable ranges. X, Y, and Z correspond to variables presented in figures 2 and 3. *100 kPa was previously used to definite icephobic surface* [22]; ***60 kPa was suggeted as low/ice adhesion surfaces* [23]; ****10 kPa was defined as the super-low ice adhesion sufaces* [24]

	X / (kPa)	Y / (g/m^2)	Z / (min)
1	100*	900	60
2	90	800	90
3	75	700	120
4	60**	600	150
5	50	500	180
6	40	400	210
7	25	300	240
8	10***	200	270
9	1	100	300

2.3 Requirements

2.3.1 Standardized testing

In order for a classification scheme to function properly, some standard method of testing is commonly chosen. In the case of ice adhesion, there is a plethora of testing methods, each with advantages and disadvantages [25], though the relating of methods to each other within a single ice type is rarely reported on and presents a challenge to the correlation of results [11,26]. Furthermore, it has recently been shown that different methods for testing ice adhesion strength results in slightly different values of ice adhesion [26], although the general trends hold so far. As previously discussed, quantitative ice accretion methods exist though, much like for ice adhesion, the methods are not standardized, making it difficult to correlate existing results. In measuring the time until accretion, however, it appears advantageous to define a standard sample size along with a standard mass to define the time-limit.

For snow adhesion, controlled laboratory testing methods are scarce but do exist [27]. As snow requires specialized equipment to realistically synthesize in a laboratory, and expensive set-ups to utilize in a controlled environment, most tend to conduct experiments *in-situ* with little to no control over ambient conditions [28,29].

General agreement on a single standard method for all testing may be difficult to obtain where many exist. Laboratories often build or buy the equipment most convenient to them and would be hard pressed to invest in a new set-up. This problem may be circumvented by very accurately correlating the results they offer, with all experimental parameters included, such that any established measuring equipment may be used. Correlating methods, however, may not be necessary for classification purposes, as proper certified classifications are most often conducted by accredited laboratories only, who have an innate incentive to invest in the proper standard equipment.

There is also a need to define all the parameters for each standard test, such as ambient temperature, relative humidity and many others. Determining these exceeds the present scope, though it appears most useful to ascribe standards that most commonly appear in the literature or that best represent the most common engineering cases.

Implementation of a classification with specified ice and snow types, as shown in figure 3, generates a list of combinations of ice and snow types. It is, however, not necessarily useful to test all three parameters for all types. For some engineering cases, e.g. a product intended only for ice accretion mitigation, it may not be necessary to perform a snow adhesion mitigation test. By testing only for relevant aspects, the cost of testing can be minimized.

2.3.2 Setting of ranges and limits

The ranges of adhesion and accretion must be set in such a way that they differentiate sufficiently for most applications. Industrial producers of equipment in need of a low ice accretion surface, should not all be forced to choose the maximum level for all applications, nor should the lowest level be sufficient for any application. We have here suggested ranges for the three variables as a starting point. Before general implementation, however, thorough reviews the state-of-the-art for each variable, as well as assessments of the needs of industrial applications, should contribute to the final ascription of integer level values. It should be discussed and debated in more detail than the present scope allows, perhaps most aptly by experts in each of the three fields and representatives from the industries that may make use of such a classification scheme.

2.3.3 Correlation database

As previously mentioned, a database of adhesion and accretion data gathered with all the methods available, could allow for a higher degree of correlation of adhesive behaviour of one type ice to another, using a single ice type test. In order to reach accuracies of prediction sufficient to provide reasonable confidence in such comparisons, however, a high level of accuracy is required in the reporting of findings. Such accuracy is not always included in publications, however, as pointed out by Work and Lian [25]. This implies that certain requirements should be placed on submission acceptance to the database which may either incentivize researchers to fulfil the requirements and presenting more accurate work or conceivably deter researchers from submitting.

2.3.4 *Administration and development*

A classification must be properly administrated to ensure that inflation of results is avoided and to ensure the integrity of the classification. This is generally accomplished by regular control and accreditation of the classifying agents, i.e. classifying laboratories and companies. Administration of this type is most commonly handled by committees such as the European Committee for Electrotechnical Standardization that administrate European Standards (EN) documents. A similar committee for crynerophobic surface classification with representatives from different facilities and fields of application might be initiated for this task.

3 Discussion

3.1 Impact of success

A classification of the type presented here is generally not motivated by advantages to academic research, but by advantages to the industry. A manufacturer of a product requiring low ice adhesion or resilience towards ice accretion, would be aided by the tool of a classification for communicating their needs and expectations to their subcontractors. It would also allow them to communicate the excellence of their product to prospective customers and thereby gain market shares. Such a tool for communication spills over to academic research, where use of a wide range of methods for analysis may not allow for accurate classification but allows for orientation of progress and milestones achieved. Communication of progress and the reaching of milestones is also here of significant importance, as reports are given to political and other organisations that distribute funding. While a widely agreed upon classification for cold precipitation would undoubtedly require significant further discussion and debate to properly establish, successfully doing so appears to be worthwhile pursuing given the advantages.

Attaining a wide agreement will naturally attract debate and opposition to various points. Successful dissemination and acceptance of a classification such as presented here could fail if confidence in it becomes too low. Therefore, a productive discourse on the details between representative experts with the greatest width of representation possible, will be vital for success.

3.2 State-of-the-art maturity

It has often been the case that snow adhesion mitigation has been lumped in as a consequential side effect of low ice adhesion. This was recently refuted [9], showing the importance of specialized engineering approaches to mitigate snow adhesion. The separation of both ice accretion and snow adhesion from icephobicity, has led to the syntax design suggested here. If more facets are separated from these three by future discoveries, the syntax may then have to be redefined.

The benefits to the industry argue in favour of implementation with the separations currently available. As understanding evolves, so too will definitions and classifications. This development has occurred with several classification schemes, including the IP code. New versions with new definitions or limits can thus be agreed upon by the administrating organization and disseminated to the world through updated documentation.

3.3 Correlation database

Correlating ice adhesion, ice accretion, and snow adhesion by type and method of analysis has the potential to fundamentally alter how their results are viewed. Placed in the context of a classification scheme, a level of structure is added whereby we may better communicate state-of-the-art and progress to the relevant audience.

The need for accurate reporting such that reported results are properly relatable, a minimum level of accuracy in reporting of variables should be demanded. For example, reported data of testing method and parameters such as ambient temperature, relative humidity, time consumption, sample mass and dimensions, has to be available as they may significantly impact the results. Maintaining such a demand for completeness and accuracy in reported data, suggests that acceptance to the database has to be moderated and therefore a moderating body is needed, such as a committee as previously mentioned. The moderation process could also be automated by a publication form with demands on reporting a number of variables which would thus allow for compilation of data and immediate presentation of the current state-of-the-art in a unified format.

3.4 Syntax reference choice

One of the main concerns discussed herein is the option to use either a standardized type of ice or to use a range of ice type classifications. While the simplified syntax shown in figure 2 carry an arguable perception advantage, the implementation of a range of classifications appears to be the more directly implementable. While ice and snow do not exist in an integer range of types, but in a continuum of variables, such as density, temperature, and age since formation, the range may be expanded to better accommodate common engineering cases.

The more easily implemented syntax presented in figure 3 thus has a significant advantage. Coupled with the classifying responsibility of certified organizations only, speaks to the advantage of the syntax shown on figure 3 over that of figure 2.

3.5 Definition of variables

Ice adhesion is traditionally defined as the lateral force per unit area required to dislodge a stationary volume of ice from a surface. Recently, this view has been challenged by a concepts such as interfacial toughness [30] and stress localization [17]. These concepts are promising but far less common and currently not generally adopted by the field. It may be that the new concepts gain wide acceptance but until then, the traditional definitions are sufficient. Snow adhesion follows the same definition and may be similarly affected by a future shift in view of adhesion.

We have defined ice accretion in a manner similar to what is commonly reported quantitatively. We are not aware of any widely accepted standard for ice accretion in the form of frost, though the reporting of time until a predetermined mass has accreted on a standardized sample size, appears an uncontroversial approach.

3.6 Future research

The present discussion has partly revolved around the need for a database to allow for the correlating of results, such that the full potential of a classification scheme may be reached. In order for that to be possible, a proper definition of what variables to demand reported, has to be defined. As accuracies of measurements may vary greatly, defining requirements for data accuracy may also be necessary.

Given the successful definition of requirements and the setting up of a repository to which one may report findings, data already available has to be vetted for applicability and added along with new data. Consolidation of the different views and methods for ice adhesion will require substantial agreement, which is not present today. In addition, snow adhesion and ice accretion are little reported on, relative to ice adhesion, and would thus require the strongest focus to establish a sufficient amount of data.

When a repository of data of sufficient accuracy and completeness is available, modelling will be required to establish the relations between types of ice and snow. This will likely also require advancements in the understanding of interfacial bonds and the mechanisms for overcoming them, especially for the less reported on mitigations of snow adhesion and ice accretion.

4 Conclusions

Successful implementation of a classification scheme, such as the one proposed herein, has the potential to enable industrial partners to communicate about requirements and expectations, as well as highlight excellence of performance.

Getting to the point of implementation still requires substantial work. The relating of results to a classification standard, requires wide comparisons to be made between available information, suggesting the need for a database of results on which to build models.

As a developing field, new information may become known that alters the view on what the classification should contain. A classification, however, can be adapted over time and the advantages to ease of communication, speak to the virtue of implementation sooner rather than later.

Two syntax alternatives have been discussed, utilizing either one standard type of ice and snow or including variable types. It has here been argued in favour of the latter as the state-of-the-art of result comparability has not yet matured to the point where the former may be employed.

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References

[1] R.W. Gent, N.P. Dart, J.T. Cansdale, Aircraft icing, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 358 (2000) 2873–2911. doi:10.1098/rsta.2000.0689.

[2] K. Savadjiev, M. Farzaneh, Modeling of icing and ice shedding on overhead power lines based on statistical analysis of meteorological data, IEEE Trans. Power Deliv. 19 (2004) 715–721. doi:10.1109/TPWRD.2003.822527.

[3] O. Parent, A. Ilinca, Anti-icing and de-icing techniques for wind turbines: Critical review, Cold Reg. Sci. Technol. 65 (2011) 88–96. doi:10.1016/j.coldregions.2010.01.005.

[4] R.E. Pawluk, Y. Chen, Y. She, Photovoltaic electricity generation loss due to snow – A literature review on influence factors, estimation, and mitigation, Renew. Sustain. Energy Rev. 107 (2019) 171–182. doi:10.1016/j.rser.2018.12.031.

[5] F. Mosher, D. Schaum, C. Herbster, T. Guinn, Analysis of causes of icing conditions which contributed to the crash of continental flight 3407, 2010.

[6] Y. Zhuo, V. Håkonsen, Z. He, S. Xiao, J. He, Z. Zhang, Enhancing the mechanical durability of icephobic

surfaces by introducing autonomous self-healing function, ACS Appl. Mater. Interfaces. 10 (2018) 11972–11978. doi:10.1021/acsami.8b01866.

[7] P. Guo, Y. Zheng, M. Wen, C. Song, Y. Lin, L. Jiang, Icephobic/anti-icing properties of micro/nanostructured surfaces, Adv. Mater. 24 (2012) 2642–2648. doi:10.1002/adma.201104412.

[8] H. Sojoudi, M. Wang, N.D. Boscher, G.H. McKinley, K.K. Gleason, Durable and scalable icephobic surfaces: similarities and distinctions from superhydrophobic surfaces, Soft Matter. 12 (2016) 1938–1963. doi:10.1039/C5SM02295A.

[9] P.-O.A. Borrebæk, S. Rønneberg, T. Li, B.P. Jelle, A. Klein-Paste, Z. Zhang, Snow adhesion on icephobic surfaces, (Submitted Publ. (2020).

[10] K.K. Varanasi, T. Deng, J.D. Smith, M. Hsu, N. Bhate, Frost formation and ice adhesion on superhydrophobic surfaces, Appl. Phys. Lett. 97 (2010) 234102. doi:10.1063/1.3524513.

[11] S. Rønneberg, J. He, Z. Zhang, The need for standards in low ice adhesion surface research: a critical review, J. Adhes. Sci. Technol. 34 (2019) 319–347. doi:10.1080/01694243.2019.1679523.

[12] L. Wang, Q. Gong, S. Zhan, L. Jiang, Y. Zheng, Robust Anti-Icing Performance of a Flexible Superhydrophobic Surface, Adv. Mater. 28 (2016) 7729–7735. doi:10.1002/adma.201602480.

[13] IEC 60529, Degrees of Protection Provided by Enclosures (IP Codes), Geneva Int. Electrotech. Comm. Ed. 2.1 (2001) 1–3. http://www.dsmt.com/pdf/resources/iprating.pdf.

[14] S. Rønneberg, C. Laforte, C. Volat, J. He, Z. Zhang, The effect of ice type on ice adhesion, AIP Adv. 9 (2019). doi:10.1063/1.5086242.

[15] K. Golovin, S.P.R. Kobaku, D.H. Lee, E.T. DiLoreto, J.M. Mabry, A. Tuteja, Designing durable icephobic surfaces, Sci. Adv. 2 (2016) e1501496–e1501496. doi:10.1126/sciadv.1501496.

[16] X. Wu, S. Zheng, D.A. Bellido-Aguilar, V. V. Silberschmidt, Z. Chen, Transparent icephobic coatings using bio-based epoxy resin, Mater. Des. 140 (2018) 516–523. doi:10.1016/j.matdes.2017.12.017.

[17] P. Irajizad, A. Al-Bayati, B. Eslami, T. Shafquat, M. Nazari, P. Jafari, V. Kashyap, A. Masoudi, D. Araya, H. Ghasemi, Stress-localized durable icephobic surfaces, Mater. Horizons. 6 (2019) 758–766. doi:10.1039/c8mh01291a.

[18] D.P. Singh, J.P. Singh, Delayed freezing of water droplet on silver nanocolumnar thin film, Appl. Phys. Lett. 102 (2013) 243112. doi:10.1063/1.4811751.

[19] Z.J. Wang, D.J. Kwon, K. Lawrence DeVries, J.M. Park, Frost formation and anti-icing performance of a hydrophobic coating on aluminum, Exp. Therm. Fluid Sci. 60 (2015) 132–137. doi:10.1016/j.expthermflusci.2014.09.003.

[20] Q. Hao, Y. Pang, Y. Zhao, J. Zhang, J. Feng, S. Yao, Mechanism of delayed frost growth on superhydrophobic surfaces with jumping condensates: More than interdrop freezing, Langmuir. 30 (2014) 15416–15422. doi:10.1021/la504166x.

[21] S. Ozbay, H.Y. Erbil, Ice accretion by spraying supercooled droplets is not dependent on wettability and surface free energy of substrates, Colloids Surfaces A Physicochem. Eng. Asp. 504 (2016) 210–218. doi:10.1016/j.colsurfa.2016.05.065.

[22] V. Hejazi, K. Sobolev, M. Nosonovsky, From superhydrophobicity to icephobicity: Forces and interaction analysis, Sci. Rep. 3 (2013). doi:10.1038/srep02194.

[23] Z. He, E.T. Vågenes, C. Delabahan, J. He, Z. Zhang, Room temperature characteristics of polymer-based low ice adhesion surfaces, Sci. Rep. 7 (2017). doi:10.1038/srep42181.

[24] Z. He, S. Xiao, H. Gao, J. He, Z. Zhang, Multiscale crack initiator promoted super-low ice adhesion surfaces, Soft Matter. 13 (2017) 6562–6568. doi:10.1039/c7sm01511a.

[25] A. Work, Y. Lian, A critical review of the measurement of ice adhesion to solid substrates, Prog. Aerosp. Sci. 98 (2018) 1–26. doi:10.1016/j.paerosci.2018.03.001.

[26] S. Rønneberg, Y. Zhuo, C. Laforte, J. He, Z. Zhang, Interlaboratory Study of Ice Adhesion Using Different Techniques, Coatings. 9 (2019) 678. doi:10.3390/coatings9100678.

[27] P.-O. Borrebæk, B.P. Jelle, A. Klein-Paste, Z. Zhang, A gravity-based method for snow adhesion measurements, (Submitted Publ. (2020).

[28] A. Weiss, H. Weiss, Photovoltaic cell electrical heating system for removing snow on panel including verification, in: Environ. Sci. Pollut. Res., IEEE, 2018: pp. 24561–24568. doi:10.1007/s11356-017-0251-4.

[29] R.W. Andrews, J.M. Pearce, The effect of spectral albedo on amorphous silicon and crystalline silicon solar photovoltaic device performance, Sol. Energy. 91 (2013) 233–241. doi:10.1016/j.solener.2013.01.030.

[30] K. Golovin, A. Dhyani, M.D. Thouless, A. Tuteja, Low-interfacial toughness materials for effective large-scale deicing, Science (80-.). 364 (2019) 371–375. doi:10.1126/science.aav1266.

Appendix B: Datasets

The Article belonging to these datasets is awaiting publication and are not included in NTNU Open

Appendix C: Concepts and definitions

Concepts and definitions

Throughout this thesis and in some other published literature, the following definitions are used.

- Adhesion – Adhesion is herein defined as the shear force per interfacial area (i.e. the shear stress) required to dislodge the adhering part, typically ice or snow in the present context.
- Atomic force microscope (AFM) – High resolution microscopy measuring the minute deflections of a cantilever probe with a laser. Deflections arise from the probe being attracted or repelled by extreme proximity to a surface.
- Building integration – Integration of photovoltaics in buildings imply that the photovoltaic module is designed to function as a replacement for a traditional building element, such as a roof tile or a cladding section.
- Bulk water ice (BWI) – The frozen state of a body of water at rest. In theory an infinitely large body of water, though commonly used to describe any frozen water from a stationary liquid.
- Cold precipitation – Water based precipitation below the melting point of water, e.g. snow, ice, frost, hail, etc.
- Condensation – A process of phase change from a vapour state to liquid state.
- Contact angle (CA) – The inner angle between a sessile droplet and the surface on which it rests. See figure 2.5.
- Contact angle hysteresis (CAH) – The difference between contact angles at the leading and trailing side of a droplet on a tilted plane. See figure 2.5.
- Crack initiation and propagation (CIP) – A process by which interfacial dislodging of adhering materials can take place.
- De-sublimation – The reverse process to sublimation. De-sublimation is a process of phase change from a vapour state to solid state without entering the liquid state though condensation.
- Frostphobic – Passive mitigation of ice crystal accretion on a surface, either through droplet freezing, freezing of condensation, or desublimation of atmospheric water.
- Heterogeneous freezing – Freezing of water in presence of third phase influence.
- Homogeneous freezing – Freezing of water devoid of third phase interference.
- Hydrophilic – A surface may be defined as hydrophilic when the static contact angle (CA) is below 90°.
- Hydrophobic – A material or surface is to be considered hydrophobic if the contact angle (CA) with water is 90° or more.
- Icephobic – Passive ice repellence, encompassing both low adhesion strength and reduced accretion of ice.
- Infinite focus microscopy (IFM) – A non-contacting 3D surface characterization method utilizing optical microscopy to create a topographical image.
- Ingress protocol (IP) – A classification of ingress protection by particulates and liquids in electronic applications.
- Low interfacial toughness (LIT) – A competing view on adhesion and its mitigation, focusing on binding energy density rather than shear force per area unit required to dislodge adhering materials.

- Liquid-like layer (LLL) – The loosely bound surface water molecules of a frozen body of water that present semi-liquid properties as a result. Also known as a quasi-liquid layer (QLL).
- Liquid water content (LWC) – The percentage of a volume of snow that remains in the liquid state.
- Mullin-Sekerka instability – A concept where a small perturbation in a small ice crystal has been seen to generate hexagonal patterned ice geometries. A theoretical explanation for the morphological trends in snow.
- Parahydrophobic – A surface is considered parahydrophobic if the contact angle (CA) to water is 150° or more and exhibits a high (not formally defined) contact angle hysteresis (CAH).
- Photovoltaics (PV) – Electricity producing devices, utilizing the photoelectric effect to convert solar radiation into electrical energy.
- Relative humidity (RH) – A measurement of how saturated a gas (typically air) is with water vapour. It is relative in the sense that the saturation limit changes with temperature of the gas.
- Return on investment (ROI) – A measure of profit per invested monetary unit, indicating the profitability such that investments can be prioritized by potential gain.
- Resting time – In the context of snow adhesion measurements, resting time indicates the time between placement of the sample on the substrate and the commencement of the tilting from the horizontal position.
- Slippery lubricant impregnated porous surface (SLIPS) – A surface design proposed for low ice adhesion applications where a typically water repellent liquid, is infused into the matrix of a substrate material and allowed to leach out to the surface.
- Snowphobic – Passive shedding of snow, i.e. low adhesion strength.
- Static friction – Also known as "stiction", this is an adhesive barrier seen before the onset of interfacial movement, also referred to as kinetic friction.
- Superhydrophobic – A surface is considered superhydrophobic if the contact angle (CA) to water is 150° or more and it exhibits a low contact angle hysteresis (CAH), typically no more than a few degrees.