The Challenge of Removing Snow Downfall on Photovoltaic Solar Cell Roofs in order to Maximize Solar Energy Efficiency – Research Opportunities for the Future

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Abstract

The challenge of removing snow downfall on photovoltaic solar cell roofs, also including solar thermal panels and walls, in order to maximize the solar energy efficiency, is investigated. A special emphasis is given on possible research opportunities for the future. As the application of building integrated photovoltaic (BIPV) products is increasing, it is becoming more important to solve this challenge in order to maximize the solar energy harvesting from buildings. In addition, a solution within this field, may also be utilized in other areas, e.g. for window roofs and traffic signs which are often concealed by snow and ice. Various ideas and possible steps towards a solution of the challenge are discussed, which may then in turn set in motion creative thinking and problem solving paths with new follow-up investigations. Several aspects with snow covering solar panels are treated and discussed, including possible paths towards a working solution. Furthermore, this work presents the compilation and discussion of an experimental method for measuring friction between snow/ice and various building roof surfaces. Some results from these experimental investigations are discussed, including a slip angle and a friction coefficient classification system for roofing types and material surfaces with respect to snow and ice.

Keywords: *Snow; Ice; Photovoltaic; Solar cell; Solar thermal; Energy.*

Content

1. Introduction and Background

1.1. Origin of Work

The origin of this work was through the collective research project "*European Performance Requirements and Guidance for Active Roofers*" (*Eur-Active Roofer* for short) during 2005-2008, where the challenge to be addressed arised from work within work package E (WP E) - Snow and Ice Load. The Eur-Active Roofer project has its origin in the increasing variety in new products such as photovoltaic (PV) systems, solar collectors, roof lights, ventilation devices, insulation and safety devices which is being introduced in roofing. The roof changes into an *active roof* where it supplies electricity and hot water while providing daylight and ventilation. Active roofs may contribute significantly to the quality of the living space under the roof.

The definition active roofs cover all roofs which are active in one way or another beyond the traditional task of protecting the inside of the building from the various climate exposure factors. Several typical active roof installations for both flat and pitched roofs are depicted in fig.1. There is an increased attention to active roofs due to the following:

- New installation types
- Increased use of installations
- Change in climate and climate loads
- Increased focus on moisture problems and indoor environment

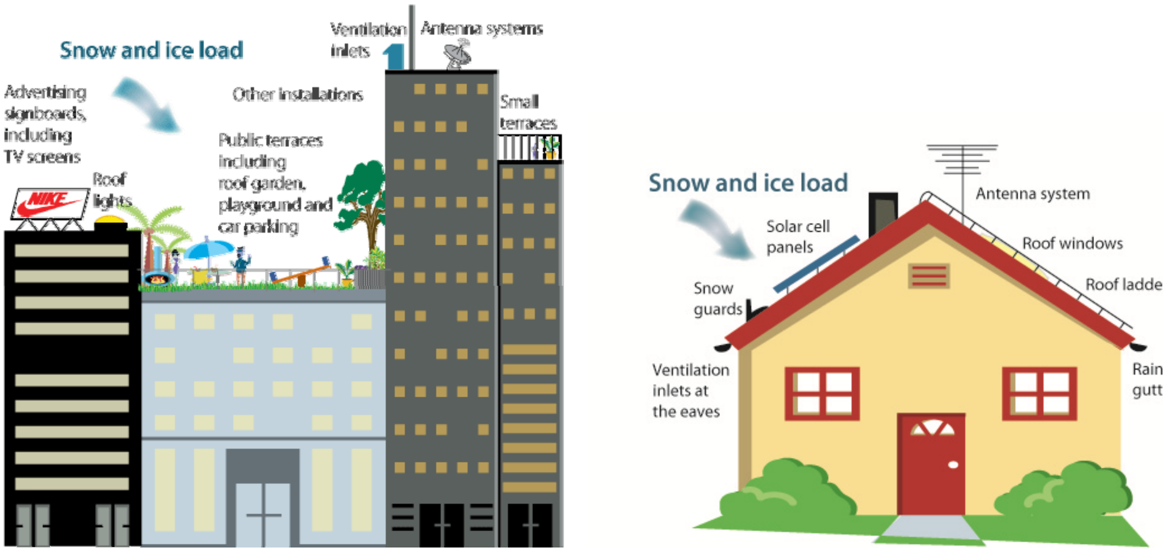


Figure 1. Various active roof installations for flat (left) and pitched (right) roofs. (Illustrations: SINTEF Building and Infrastructure).

1.2. Background Snow and Ice on Roofs

Traditionally, roofs have been designed to keep the snow in its place on top of the roofs. However, solar cell roofs should ideally have no snow covering the cells, in order to maximize the solar cell energy production. Other active roofs, such as roof windows, may also require as little snow as possible on top of them.

Solar cell roofs covered by snow during long periods in the winter, will suffer from a substantial decrease of both energy and cost effectiveness, at the time of the year when the energy is most needed. Devoting parts of the roof for snow accumulation will, in addition to decreased energy generation due to less solar cell area, lead to new strains on these parts of the roof, both with respect to building physics problems like moisture, freezing, thawing, etc., and with respect to structural building and roof properties. Some typical roof problems, caused by snow and ice, which may affect active roof installations, are shown in figs.2-6. Modifications of the roof surfaces may easily alter the snow friction as depicted in fig.5 and fig.6, e.g. resulting in unexpected snow avalanches from the roof. Ross and Usher [63-64] and Ross [65] address some of the issues related to snow accumulation and icing on photovoltaic panels.

Figure 2. Snow hanging from roof and covering the glass facade of a school building (left) and rain gutter at the eaves completely full of ice (right). (Photo: SINTEF Building and Infrastructure).

Figure 3. Large icicles covering the glass facade at a shopping centre (left) and close-up of the right part of the left photo, where the ice is completely covering this part of the glass facade (right). (Photo: SINTEF Building and Infrastructure).

Figure 4. Large icicles in front of the glass facade of a school building, covering the windows and representing a hazard to the children (left) and large icicles blocking the window and representing a hazard to the people below (right). (Photo: SINTEF Building and Infrastructure).

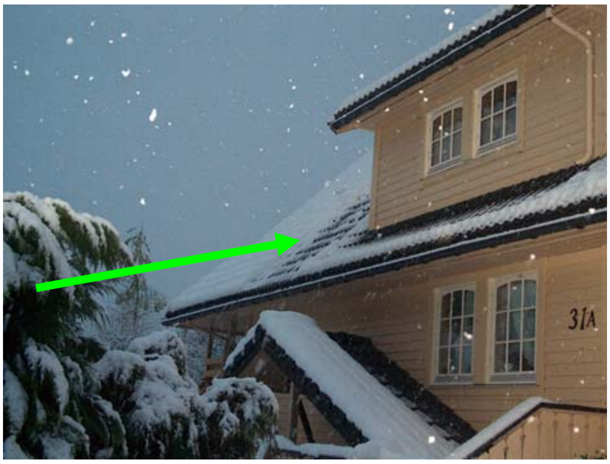


Figure 5. The above house had not had a single snow avalanche from the roof in 20 years, but after painting the roof tiles the first snow avalanche took place (at arrowhead). (Photo: NTNU).

Figure 6. Right part of the roof of the above building was exchanged with smoother roof tiles, resulting in lower snow friction and a rather peculiar view from one of the windows. (Photo: SINTEF Building and Infrastructure).

Both new material surface technologies and new architectural roof designs may play important roles in the task of avoiding snow from staying on the active roof installations. This task will also become more important with increased use of building integrated photovoltaic (BIPV) systems, see e.g. the state-of-the-art reviews and future research possibilites on BIPVs by Jelle et al. [34], Jelle and Breivik [35] and Jelle and Breivik [36].

Naturally, the discussions within this article may also be valid for other systems than photovoltaic solar cell roofs. Solar thermal panels, window roofs and various information signs (e.g. traffic road signs) are some examples. In additon to pitched roofs, the discussions may then also be applicable to walls and vertical solutions. Note in this respect the various application and technology areas for fenestration of today and tomorrow (Jelle et al. [33]), including windows being able to control the solar radiation transmission throughput, i.e. smart windows (Baetens et al. [2], Granqvist [21-22], Granqvist et al. [23], Jelle and Hagen [30-31], Jelle et al. [32], Lampert [44-46]). Potential new hazards, such as downfall of snow and ice, representing a risk for people passing beneath the roof, and undesirable snow accumulation or snowdrift, e.g. in front of building entrances and pathways, have to be evaluated.

1.3. Objective of Work

Hence, with background in the above, the main objective in this work is to address and investigate the challenge with snow downfall on photovoltaic solar cell roofs, also including solar thermal panels and walls, in order to maximize the solar energy efficiency, with a special emphasis given on possible research opportunities for the future. A solution within this field, i.e. snow and ice sticking to solar cell panels, may also be utilized in both similar and totally different fields, e.g. from window roofs to traffic signs which are often concealed by snow and ice, and furthermore to the serious threat of ice build-up on electrical power transmission lines. In addition, this work also presents the compilation and discussion of an experimental method for measuring friction between snow/ice and various roofing surfaces, where some results from these experimental investigations are discussed, including a slip angle and a friction coefficient classification system for roofing types and material surfaces with respect to snow and ice.

As will be discussed later, this work aims at removing the snow and ice, or rather inhibiting the snow and ice from forming at all, at e.g. the solar panel (solar cell and solar thermal collector) surfaces. Therefore, as there should be no snow and ice at the solar panel surfaces, there should ideally neither be any solar efficiency influences in this respect to be calculated. Hence, it is outside the scope of this work to estimate solar cell efficiencies with respect to various snow coverages. However, for some information on these issues see aspects within Becker et al. [4] and Michigan Tech [52]. In addition, as it is sought for a solution which does not consume any extra energy neither use any solar energy which otherwise could have been exploited by the solar panels, there is ideally neither any economical cost issues to be calculated with respect to the energy achieved and cost paid due to snow and ice coverage. There will naturally be cost issues regarding the material and solution manufacturing issues, but these may of course not be calculated before a valid solution is operable. Thus, it is about time to address these very research issues now, which is hence carried out within this article.

1.4. Two Snow Philosophies

The two contradictory snow philosophies may be written as follows:

- **Philosophy 1 – Keep the snow on the roofs**
  - Normal roof solution in order to avoid hazardous snow downfall from the roof, snow/ice roof damages and accumulation of snow in front of entrances, pathways, etc.
- **Philosophy 2 – Remove the snow from the roofs**
  - Increased solar cell efficiency when not covered by snow.

Some possible solutions for snow philosophy 2, i.e. remove the snow from the roofs in order to increase solar cell efficiency, may be written as:

- **Philosophy 2 – Remove the snow from the roofs – Possible solutions**
  - New advanced material or surface technology, e.g.
    - ”Zero” friction for snow and ice – Immediately removal of falling snow.
    - Self-heating materials (e.g. from ambient infrared radiation or solar radiation)
    - Self-cleaning surface.
  - New roof design.
  - Others?

Various possible solutions for removing the snow from the building roofs are elaborated further in the chapter about possible paths towards a working solution.

1.5. Complex Experimental Method

Within the work presented here, snow and ice friction experiments have been carried out, mainly in order to measure the snow and ice slip angle for roofs and determine the friction coefficient between snow and various roofing materials. The complex matter of snow and ice involves a vast number of factors may and will influence the snow and ice friction experiments. Hence, care has to be taken by carrying out these experiments and the evaluation of them with respect to real outdoor conditions. That is, these friction experiments involving snow, ice and roofing substrates represent a very complex method, not due to friction experiments in general as these are relatively simple, but rather due to the complex nature of snow and ice which may be summarized as follows:

- Snow and ice exist in countless variations.
- The snow and ice nature is dependent on a vast number of factors.
- Variable indoor and outdoor climate conditions complicate the snow/ice matters..
- There is a complex interaction between the snow/ice and roofing surface.

1.6. The Complex Nature of Snow and Ice

Investigating these matters more in depth, snow and ice is a material of a complex nature due to the following reasons:

- **Snow and ice in countless variations**
  - The Lapps and Eskimos are commonly believed to have numerous words for different types of snow and ice, as a matter of life and death to have been able to survive in their relatively harsh environments for centuries, but this belief is disputed by some linguists and others.
  - Magono and Lee (Gray and Male [24]) have classified 80 different natural snow crystals, where particles such as ice pellets and hail are not included (see fig.7).
  - Snow and ice interactions with various substrates and climate conditions in general create yet another set of numerous snow and ice types.
- **Dependent on a vast number of factors, e.g.:**
  - Atmospheric conditions.
  - Climate conditions.
  - Weather exposure.
  - Temperature.
  - Pressure.
  - Storage conditions.
  - Sunshine.
  - Pollutions.
  - Time.
  - Etc.
- **Variable indoor and outdoor climate conditions**
  - What experimental conditions to choose?
  - Numerous climate conditions exist, and a given set has to be finally chosen in order to be both feasible and to cover the most relevant and frequently occuring conditions.

  - The outdoor conditions in particular, e.g. the temperature and relative humidity at the snow/ice and roofing interface, are playing a major role.
- **Snow and ice interactions with roofing substrate**
  - How to simulate these interactions in the best way, both with respect to the real outdoor situation and to a practical experimental method, the latter one with regard to both relative comparison and absolute determination experiments of the friction coefficient?
  - Temperature and relative humidity conditions at the snow/ice and roofing substrate interface may play a crucial role.
- **Snow is a *very hot* material**
  - Relatively large and fast material changes around the melting point at 0°C (e.g. numerous snow/ice/water variations).
  - Compare with many other solid state materials with much higher melting points, e.g. iron at 1538°C.

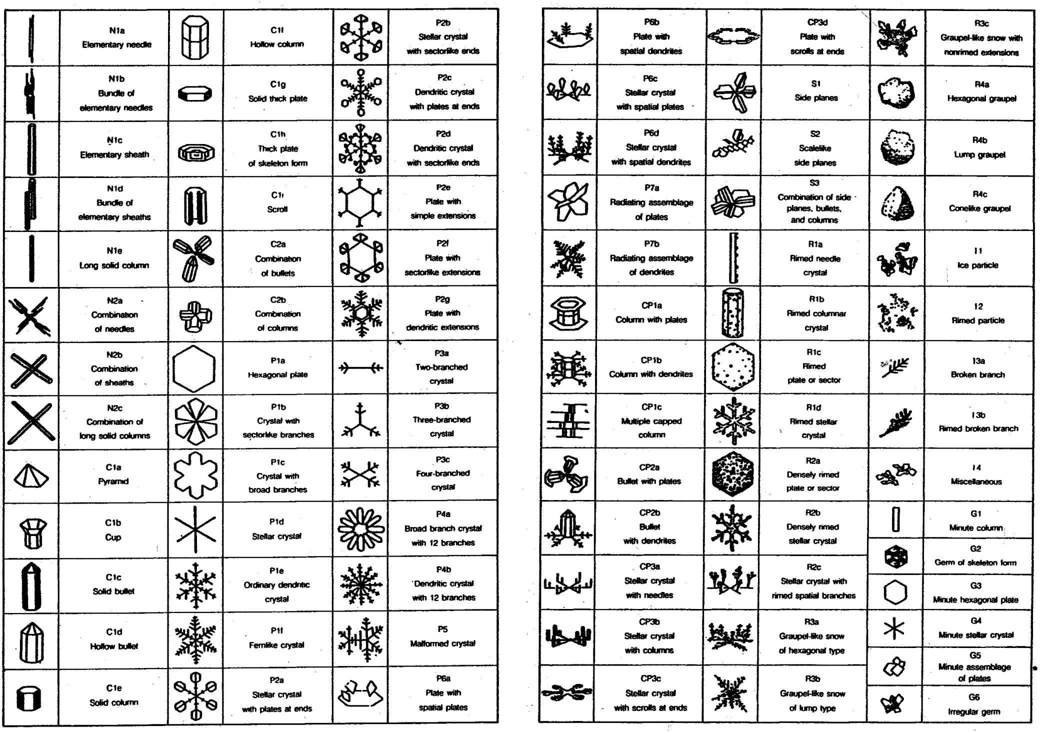


Figure 7. Snow crystal classifications according to Magono and Lee (from Gray and Male [24]).

2. Development of a Snow Friction Method – Experiments, Results and Discussion

2.1. General

The development of a method for measuring the friction coefficient between snow/ice and various roofing surfaces is presented and discussed in the following. Miscellaneous experimental details and topics are treated and related to the measured results, also including a classification framework of roofing type or material surface according to their measured slip angle and snow friction coefficient. The performed laboratory experiments are also presented in order to visualize parts of the problem task of how to remove snow downfall on photovoltaic solar cell roofs. Besides the visualization part, the various experimental details may also initiate creative thinking within this field.

2.2. Measurement of Friction between Snow and Roofing

Several experiments have been performed with the primary aim to determine the friction coefficient, both static and dynamic, between snow and various roofing surfaces, where in this study so far glass represents the low friction end of materials. These experiments are carried out using a Lloyd 10K tension machine for the horizontal plane applied pulling force method and a tailor-made friction table for the inclined plane slip method according to SINTEF Method 169 [67]. It is emphasized that due to the complex nature of snow and ice, a vast number of factors may and will influence the snow and ice friction experiments. Hence, care has to be taken by carrying out these experiments and the evaluation of them with respect to real outdoor conditions.

Two methods for measuring the friction coefficient between snow and roofing, and also various roof installations, are given in SINTEF Method 169, ”Measurement of Friction between Snow and Roofing” [67]. Both static (starting, resting) and dynamic (sliding, motional, kinetic) friction coefficients are treated, in Method A, ”Fricton Coefficient Determination between Snow and Roofing by Horizontal Plane Applied Pulling Force Method” and Method B, ”Fricton Coefficient Determination between Snow and Roofing by Inclined Plane Slip Method”, respectively (fig.8 and fig.9).

Method A (horizontal plane) gives the static and dynamic friction coefficient between the roofing and packed snow, and also between the roofing and packed snow with an under layer of ice. This method is suited for roofings with coarse surfaces.

Method B (inclined plane) gives the static friction coefficient between the roofing and packed snow, and also between the roofing and packed snow with an under layer of ice. This method is suited for roofings with coarse and smooth surfaces. The method is not well suited for slip angles between 0.1° and 1.0° (friction coefficients between 0.002 and 0.02), and is not applicable for slip angles below 0.1°.

Note that the methods are relatively new and are still in the testing phase. For the time being they are therefore recommended only for preliminary experiments. Friction coefficients from these experiments should therefore not uncritically be transferred to real situations.

For ***method A*** the friction coefficient μ for the roofing is given by the following (fig.8):

$$\mu = R/N = F/G = F/(mg) = a/g = v^2 / (2gx) = 2x / (gt^2) \qquad (1)$$

where

R = friction force parallel with the sample surface
N = normal force on the sample surface
F = applied pulling force parallel with the sample surface
G = mg = gravitional force
m = mass of sample
g = 9.81 m/s^2 = gravitional acceleration
a = acceleration of sample
x = distance the sample travels during time t
v = velocity of sample after time t
t = time

For ***method B*** the friction coefficient μ for the roofing is given by the following (fig.8):

$$\mu = R / N = \tan\theta \qquad (2)$$

where

R = friction force parallel with the sample surface
N = normal force on the sample surface
θ = slip angle = angle of inclination between horizontal plane and inclined plane when the snow sample begins to slip (slide downwards) the inclined plane

In general the static and dynamic friction coefficient are denoted μ_s and μ_d, respectively, where in general $\mu_s > \mu_d$. Photos from actual snow friction experiments are given in fig.9.

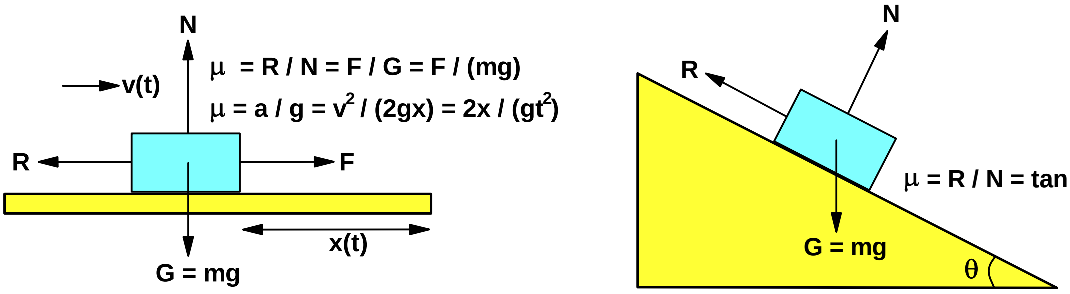


Figure 8. Friction coefficient determination between snow and roofing by method A (left) horizontal plane applied pulling force method and method B (right) inclined plane slip method. (Illustrations: SINTEF Building and Infrastructure).

Figure 9. Friction coefficient determination between snow and roofing by method A – horizontal plane applied pulling force method (first photo to left) and method B – inclined plane slip method (three photos to right). (Photo: SINTEF Building and Infrastructure).

The principle for method A is measurement of how large applied pulling force is necessary in order to pull a snow sample along a horizontal roofing, in addition to the gravitional force the snow sample is exerting normal to the roofing. The friction coefficient μ is found for each single measurement by dividing the applied pulling force F by the snow sample weight $G = mg$ (eq.1). The static friction coefficient μ_s is normally determined from the maximum measured applied pulling force before the snow sample begins to slide. Freezing between roofing and snow, in addition to force versus time or distance saw tooth pattern (see e.g. fig.10), may complicate matters, in which case the top of the second force peak (instead of the first one) may be used for calculation of the static friction coefficient (2nd force peak $\Rightarrow$ "μ_s"). The dynamic friction coefficient μ_d is normally determined from the mean value of the applied pulling force along a given sliding distance. For the snow/ice on roofing substrate this may also be subject to discussion.

The principle for method B is measurement of how large inclination angle between the horizontal plane and inclined plane which is necessary for a snow sample to start sliding downwards the roofing. The friction coefficient μ is found for each single measurement from $\mu = \tan\theta$ where θ is the slip angle (eq.2). This is the static friction coefficient μ_s. Further details, supplied with additional photos, are given in the method (SINTEF Method 169 {66]).

2.3. Snow Friction Results and Discussion

Various roofing products with different surfaces, also including glass, have been subjected to snow friction experiments according to SINTEF Method 169 method A and method B [67] in order to determine their snow friction coefficients. These experiments and the evaluation of the results form the basis for the classification framework carried out in Table 1, where roofing types or material surfaces are classified according to their measured slip angle θ_{meas} and snow friction coefficient μ_{meas}. Note that the given values in Table 1 are example values in order to visualize the application and dynamics of the table. Hence, these values are therefore subject to changes. In addition, Table 1 show a few bold red example values indicating that the measured values do not fulfill the recommended values, e.g. as given in SINTEF Building Research Design Sheet 525.931 [68]. Also note that the phrase *recommended* values might be changed to *required* values.

Table 1. Classification framework of roofing type or material surface according to their measured slip angle and snow friction coefficient. The bold red example values indicate that the measured values do not fulfill the recommended values.

Slip angle of roofing or roof installation						
θ	**Type of roofing or material surface**	θ_{meas}	θ_{rec}	μ_{meas}	μ_{rec}	**Desirable to keep snow on roof ?**
Very small	Glass Roof windows Solar cell panels Solar thermal panels BIPVs	0.10 0.12 0.17 0.94 0.19	≤ 3°	0.002 0.002 0.003 0.02 0.003	≤ 0.05	no
Small	Smooth roofing with no need for snow removal	**2.3**	≥ 3°	**0.04**	≥ 0.05	yes
Moderate	Steel plates Brick tiles Polymeric roofing Slates	**2.7** **3.5** 16 23	≥ 15°	**0.05** **0.06** 0.3 0.4	≥ 0.3	yes
Large	Rough concrete tiles Granulated bitumenous roofing Granulated steel	31 36 28	≥ 27°	0.6 0.7 0.5	≥ 0.5	yes

Note 1: The given values in the table are meant as example values to illustrate the application and dynamics of the table, and are therefore subject to changes.

Note 2: See also SINTEF Building Research Design Sheet 525.931, ”Snøfangere” (Snow Guards) [68].

Figure 10 depicts an example of an applied force versus time curve during a friction experiment performed on a roofing sample employing the horizontal plane applied pulling force method (method A, SINTEF Method 169 [67]). The depicted curve does also clearly show the saw tooth pattern mentioned in the previous subchapter. The first (large) force peak in fig.10 is due to the large force which is needed to break the snow/ice slab loose from the roofing substrate due to freezing. The saw tooth pattern during pulling of the sample arises from a complicated sample-substrate interface undergoing various changes, i.e. freezing/thawing with liquid water and ice phase change formations, breaking or smoothing of the snow/ice slab undermost surface as it is pulled along the roofing surface, and finally, depending on the type of roofing sample, breaking or smoothing of the roofing surface as it experiences the pull of the snow/ice slab on top of it. The roofing surface roughness does also play an important role in this respect. Thus, these aspects complicate the determination of an exact and absolute or true friction coefficient. Relative and comparative investigations of friction coefficients are fully feasible, though. Naturally, several runs are carried out in order to calculate a representative average value with its corresponding uncertainty.

With referral to the saw tooth pattern in fig.10, and which complicates the matter at hand, it is noted that the situation at the beginning of the pulling of the snow/ice slab is different from the situation at the end of the experiment. That is, the undermost surface of the snow/ice slab undergoes changes as many of its irregularities may be broken or smoothened during the pulling on top of the roofing sample, and as also mentioned above, irregularities in the roofing surface may also be broken or smoothened. This also means that for each new applied force versus time run, a new snow/ice slab sample has to be used. A smoothening of surfaces would normally lead to a decrease in the the friction coefficient, which as a general trend within the given time frame is not observed in fig.10. Then the observed saw tooth pattern might be explained or partly explained by that the breaking of irregularities creates new irregularities being able to maintain the friction between the snow/ice slab and the roofing surface. Furthermore, the not observed decrease of friction coefficient in fig.10, while still observing the saw tooth pattern, may also be accounted for by a combination of uneven and rough surfaces with many small irregularities giving rise to a multiple of decreases and increases as the snow/ice slab slides on top of the roofing sample, with the freezing/thawing of water/ice/snow mixed into the system. Hence, care should be taken when carrying out friction experiments with snow and ice on various roofing surfaces.

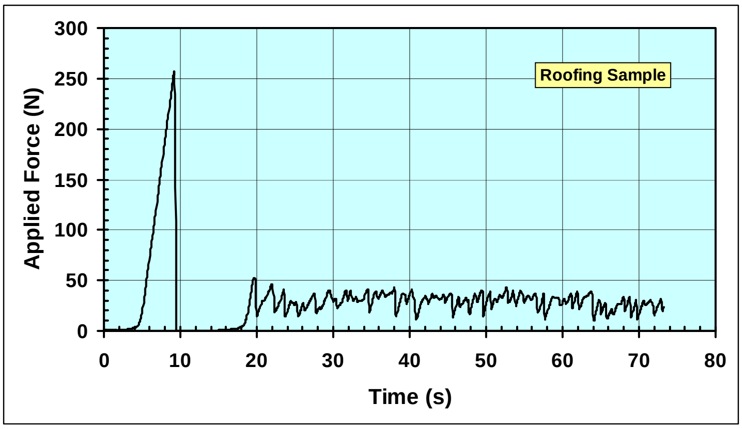


Figure 10. Example of an applied force versus time curve during a friction experiment performed on a roofing sample employing the horizontal plane applied pulling force method, also clearly depicting the saw tooth pattern mentioned in the previous subchapter.

For example, when looking into Table 1, for a solar cell panel it is not desirable to keep the snow on the roof, i.e. the measured slip angle and snow friction coefficient should be equal to or lower than the recommended values 3° (θ_{rec}) and 0.05 (μ_{rec}), respectively, in order to remove the snow from the solar cell panel. As is seen from Table 1 this is fulfilled for the actual solar cell panel with example values 0.17° (θ_{meas}) and 0.003 (μ_{meas}). Again, note that the recommended values θ_{rec} and μ_{rec} may be subject to change.

For the brick tiles, however, it is desirable to keep the snow on the roof in order to avoid snow downfall with the risk of injuring people and blocking entrances and similar, i.e. in accordance with the normal snow philosophy for roofs. That is, for the brick tiles the measured slip angle and snow friction coefficient should be equal to or larger than the recommendedvalues 15° (θ_{rec}) and 0.3 (μ_{rec}). In this case the measured example values 3.5° (θ_{meas}) and 0.06 (μ_{meas}) are marked in a bold red colour as they do not fulfill the recommendations, i.e. the actual brick tiles do not exhibit large enough friction towards snow.

During snow friction experiments with various roofings and material surfaces, it was observed that the snow slab had frozen to the substrate surface. The measured slip angle then naturally do not represent the slip angle for a normal snow sliding situation giving the real snow versus actual substrate surface friction coefficient. Nevertheless, this situation is a common occurring situation at both laboratory and outdoor real-life conditions, thus the experimental investigations need to embrace these conditions too. Hence, these issues make it considerably harder to find an answer and a solution of the question asked in the title of this article. That is, to avoid snow and ice covered solar cell roofs, the problem or challenge is not solely a snow and ice friction topic, but very importantly an issue related to adhesive forces (e.g. electromagnetic or electrostatic in nature) between the solar cell surface and the snow and ice covering it. See further discussion in the next chapter, including figs.11-15.

3. Possible Paths towards a Working Solution

3.1. Various Paths to the Solution

In the following various possible paths towards a working solution will be presented. Some of the solutions may in the end prove neither to be theoretically possible nor of practical interest at all. But even these solutions or ideas may lead to new advances within this field. The thoughts of some, even if they are ”wrong”, may initiate and stimulate to further thinking by others, thus leading to even further discussions and hopefully resulting in new insight and discoveries within this area, i.e. brainstorming. And to have a real strong *storm of brains* it is important to have many skilled and creative brains with both similar and different backgrounds. The different paths presented here may show to be fruitful in the near or far future, or not at all. Nevertheless, it is the hope that by presenting these different paths, they may initiate a process which eventually will lead to success. The solution when it is found may be based on one of the paths presented here, it may only have some elements from one of the paths, or it might be something totally different. Whatever the final solution, we have started to walk the road or path towards it.

As a sidestep it should be noted that although it is claimed in science that it is just as important to ask the right questions as to find the correct answers, this is rarely or never used in the scientific journals. Answers and results are usually presented, not the questions and possible solving-strategies. Hence, a very powerful tool or means at the hands of the scientific community is barely not exploited at all. That is, to initiate and contribute to write articles in a questioning way in order to solve specific scientific work tasks in various fields will be important. In this way there will be created an atmosphere and a worldwide forum for researchers and scientists utilizing the high quality and impact of traditional scientific journals in a new way. Even if there exists numerous discussion forums, e.g. on the internet, it is still the traditional scientific journals which are regarded as the most prestigious publishing media with the highest impact.

Figures 11-13 demonstrate that under certain climate conditions snow and ice can really be firmly adhering to solar cell and various glass surfaces even at large inclination angles. Snow accumulation and frost formation on solar thermal panels (solar collectors) are shown in fig.14 and fig.15 for two different collectors. See also fig.27 for ideas.

It should be noted that a solution within this field, i.e. snow and ice sticking to solar cell panels on walls and roofs, may also be utilized in both similar and totally different fields. As an example, traffic signs along car roads may be mentioned. The information on these signs, e.g. car speed limits, is often concealed for road-users as they are covered by snow or ice under different climate conditions, even if, naturally, the road signs have vertical surfaces.

Figure 11. Snow covering a solar cell panel at an inclination angle of 70º. Day 1, blue sky, -19ºC and clean panel → Day 2, light clouding, fresh snow, -13ºC ⇒ Panel covered with snow. (Photo: NTNU).

Figure 12. Snow covering almost vertical car windows. (Photo: SINTEF Building and Infrastructure).

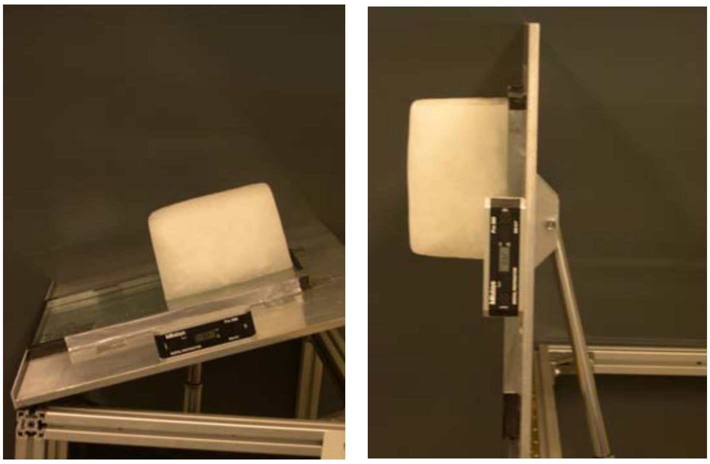


Figure 13. A snow/ice slab firmly sticking to the glass surface of an insulated window pane even at an inclination angle of 90º during a laboratory experiment. (Photo: SINTEF Building and Infrastructure).

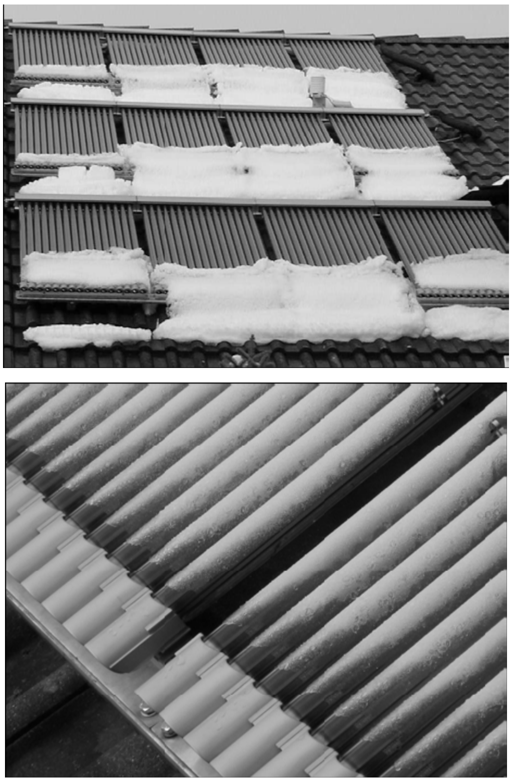


Figure 14. Snow (top photo) and frost formation (bottom photo) covering solar thermal panels (solar collectors) (Trinkl et al. [73]).

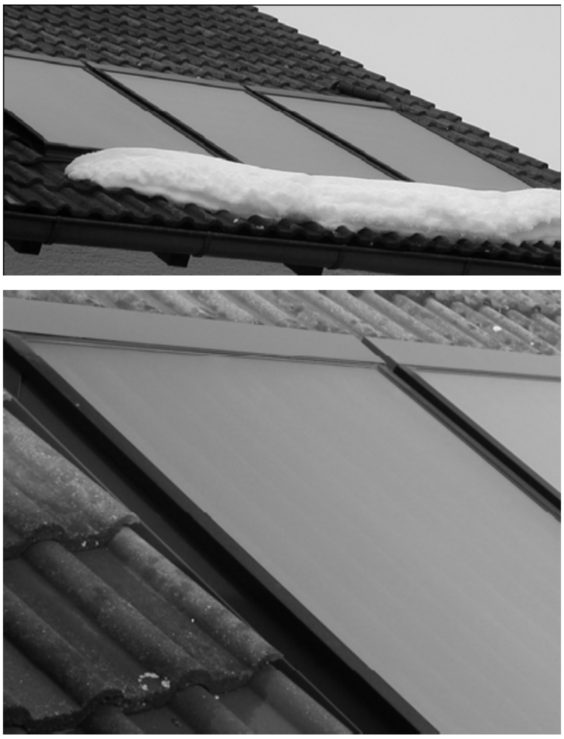


Figure 15. Snow (top photo) and frost formation (bottom photo) covering solar thermal panels (solar collectors) (Trinkl et al. [73]).

3.2. The Non-Viable Electrical Heating Cable Solution

Whenever you discuss the problem with snow and ice covering solar cell panels, in whatever forum, you can be sure that someone will mention electrical heating cables as a solution, even if you during the presentation of the problem to be addressed, have stressed that we are searching solutions which do not consume additional energy or using energy which otherwise would have have been utilized as an energy gain in the actual building (e.g. using solar energy in a wavelength range which otherwise would have been utilized to produce electricity).

Electrical heating cables may be regarded as a possible and acceptable solution in certain circumstances. However, such a solution is not considered as viable by many due to the increased energy consumption. So, just to be clear, even if electrical heating cables may currently seem to be the only solution in some cases, they do not represent a solution we are searching in this context. The heating cables consume energy.

3.3. The Non-Viable Heat Loss Solution

In order to be consistent and clear, using the heat loss through roofs to melt the snow and ice is of course not a viable solution in this context either, as the goal will be to construct and develop buildings with as low energy loss as possible in regions with a heating demand. Note that there is and will be an increased focus on low energy loss in future buildings.

3.4. The Architectural Solution

Is it possible to make an architectural solution which may somehow remove the snow on the solar cell panels? What (physical) principles could an architectural solution exploit? Various paths may be sought.

May wind be utilized in this respect? But what when there's no wind? Some kind of air stream? An air flow caused by what? And with no extra energy consumption? May the snow be taken away already before it is hitting the solar cell surface? How? Wind? Air stream? Some kind of repulsion?

Note that a working solution of course has to ensure that no large and thereby hazardous snow amounts can fall down on people. For an ideally working solution this should not be any problem as the snow is envisioned to slide off the solar cell panels continously in small amounts. For safety reasons, snow guards which will stop downfall of large snow blocks should be used. However, the snow which is removed from the solar cells on the roofs, should not be allowed to accumulate in front of entrances, pathways, etc. In addition, a working solution must not cause snow/ice roof damages, e.g. at the rain gutter.

3.5. The Water Solution

Is it possible to use water, which may give away some heat, in some way to remove snow and ice from the solar cell panels? Or even better, to apply water in such a way that from the beginning snow and ice will not stick to the panel surface? Of course, the water application must not require any energy consumption, e.g. during water distribution, nor must it involve any heat loss which could have been utilized otherwise. Such solutions might be a bit complicated with many components, but nevertheless it is mentioned in order to maybe help contributing to create new ideas and solutions.

3.6. The Low Friction Non-Sticky Surface Immediate Removal Solution

One may envision that the solar cell panel surface has so low friction coefficient with respect to snow, that the snow downfall on these panels will slide off immediately as the snow crystals hit the panel surface. Naturally, the efficiency of this snow removal will depend on many factors, e.g. the inclination angle of the solar cell panels. And what about air moisture condensation and freezing onto the solar cell panels, i.e. frost formation? May this also be taken care of?

What kind of material or coating could achieve this goal of a low friction non-sticky surface, and both these properties with respect to snow, ice and freezing/melting water? Maybe this material or coating already exist? Or do we have to invent/manufacture it? Think of for example the invention of teflon, i.e. polytetrafluorethylene (PTFE), which has solved many non-sticky work tasks. In our case of snow removal we need an even more extreme material. Might advances in nanotechnology be exploited? See also fig.27 for ideas. This might present a challenge to material scientists and alike, i.e. does such a low friction non-sticky surface material exist or are there any ideas about how to make it? Could the adhesive forces (e.g. electromagnetic or electrostatic in nature) between snow/ice and various roofing surfaces (e.g. solar cells) be explained and modelled, and thus making us able to utilize this knowledge to control and tailor-make solar cell surfaces where no snow or ice will be attached?

3.7. The Self-Cleaning Surface Solution

So-called self-cleaning window glass panes already exists commercially, which are supposed to decrease the need for manual cleaning substantially. Most of these glass panes usually work by employing a photocatalytic coating (e.g. TiO_2) on the outer glass surface, where this coating reacts with the ultraviolet (UV) solar radiation to break down organic dirt. Thereafter rain water spreads evenly over the hydrophilic surface and runs off in a ”sheet” taking loosened dirt with it, hence drying quickly without leaving stains or streaks, e.g. as illustrated in fig.16 (Pilkington [61]). May these materials and technology give any ideas on how to solve the snow removal issue? See also fig.27 for ideas. Chabas et al. [9] have investigated the behaviour of self-cleaning glass in an urban atmosphere. Also note the study by Midtdal and Jelle [53] on self-cleaning glazing products where a state-of-the-art review has been presented along with future research pathways.

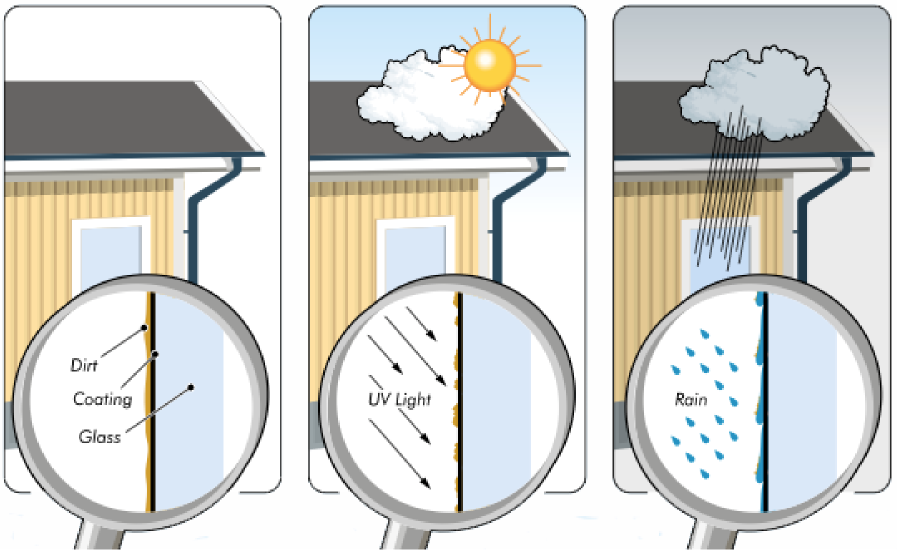


Figure 16. Illustration of the working principle of a self-cleaning window pane (Pilkington [61]).

3.8. A Closer Look at the Self-Cleaning Effect

It is not within the scope of this overview to look into all details of possible self-cleaning solutions. Nevertheless, as the self-cleaning effect may present important larger or smaller parts of a possible working future solution, or may give inspiration and ideas to forthcoming solutions yet to be discovered and investigated, it is appropriate to have a closer look at the self-cleaning effect and give references to the miscellaneous research paths being explored.

In order to achieve a self-cleaning effect several different strategies are applied and pursued for further investigations today. These strategies may be divided into the following surface characteristics:

- Photocatalytic hydrophilic surface
- Superhydrophobic or ultrahydrophobic surface
- Coarse microstructured or nanostructured surface

As we will see in the following there are links between superhydrophobicity and a structured coarseness of a surface.

Commercial self-cleaning products may according to their operational state when purchased be divided into the following two categories (Midtdal and Jelle [53]):

- Factory-finished products
- User-finished products

The factory-finished products cover all factory produced glazing products, e.g. windows and doors, on which a self-cleaning surface is already operational when purchased. The user-finished (i.e. user-do-it-yourself) products, involve liquid products, either in form of a spray or a roll-on applicator, which can be applied by the user to existing glass surfaces to yield a self-cleaning coating or film on top of the regular glass pane (or other materials and products). The commercial factory-finished products are normally based on photocatalytic hydrophilic coatings or surfaces, whereas the user-finished products are usually based on the creation of hydrophobic coatings on the desired surfaces. Figure 17 depicts the different water drop shapes on a hydrophilic and a superhydrophobic surface (Antonini et al. [1]).

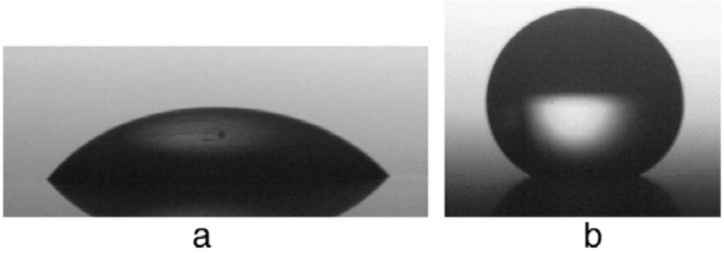


Figure 17. Water drop on (a) a hydrophilic surface and (b) a superhydrophobic surface. The drops have the same volume equal to 11.5 µl corresponding to a spherical drop with diameter 2.8 mm (Antonini et al. [1]).

The photocatalytic hydrophilic self-cleaning products of today normally apply titanium dioxide (TiO_2) as the photocatalytic layer, utilizing UV solar radiation to break down chemical bonds in organic dirt fastened on the surface, thereafter utilizing rain water to wash off the loosened dirt over the hydrophilic surface. In this respect it should be noted that a photocatalytic layer like e.g. TiO_2 is not able to break down the chemical bonds in inorganic dirt (e.g. sand), and it is also a question how (perfect) hydrophilic a surface may be made and how long that surface will maintain its hydrophilic characteristics. As examples the studies by Eiamchai et al. [13], Mellott et al. [50] and Miyashita et al. [55] may be noted.

Superhydrophobic or ultrahydrophobic self-cleaning products are aiming at repelling the water from their surfaces. However, an investigation by Keranen [38] found through a 24-month exposure test of vertically installed self-cleaning glazing products, that hydrophobic glass surfaces, in comparison with factory-produced hydrophilic self-cleaning glass, were considerable less clean. In fact, the hydrophobic glass surfaces were even found much less clean than ordinary clear float glass. Nevertheless, considering the results by Fürstner et al. [19], the superhydrophobic property of an artificial lotus leaf (Nelumbo nucifera) was found to have excellent self-cleaning abilities, with a contact angle of about 158°. The study also tested artificial metal surfaces with superhydrophobic abilities with a contact angle of almost 165°, which was found to remove over 98 % of the contaminants on its surface after it was subjected to artificial contamination and rinsing. Furthermore, some other metal specimens removed close to 100 % of the contaminants. These results by Fürstner et al. [19] indicate that it could be possible, with the technology today, to tailor-make self-cleaning superhydrophobic products, which could exhibit far better self-cleaning properties than those reported by Keranen [38]. That is, superhydrophobicity may be a self-cleaning solution strategy after all.

Specific coarse microstructured or nanostructured surfaces may be tailor-made in order to obtain self-cleaning properties by various principles. One example is seen in fig.18 comparing (left) a smooth surface where particles are merely redistributed by water droplets, to (right) a rough surface where particles adhere to the water droplets and are removed from the surface (Barthlott and Neinhuis [3]). Another example is by Gerber and Tuma [20], who present a self-cleaning surface structure invention by artificially creating a material surface on which the physical exterior structure has or develops a capillary effect, i.e. added liquid is pressed from the capillaries, which then is able to remove contaminant particles on its escape from the material surface, thus inducing a self-cleaning effect. Figure 19 shows various states a drop may have on a surface, illustrating an increased hydrophobicity (and larger contact angle) on a coarse surface compared to a smooth surface, also depicting the Wenzel state, the Cassie-Baxter state and a combined state (Antonini et al. [1]). Note that in the Cassie-Baxter state there are vapour pockets trapped between the surface grooves and the liquid drop. Contact angles may be calculated according to Young's equation, the Wenzel equation and the Cassie-Baxter equation (Antonini et al. [1]). For further information and details on hydrophobicity and the Cassie-Baxter state it is referred to the available literature, e.g. see the studies by Antonini et al. [1], Bhushan and Jung [5], Cansoy et al. [7], Cao et al. [8], Cheng et al. [11], Dash et al. [12], Erbil and Cansoy [16], Hsu et al. [28], Kulinich and Farzaneh [41], Öner and McCarthy [58], Sun et al. [70], Victor and Erb [75] and Zheng et al. [81].

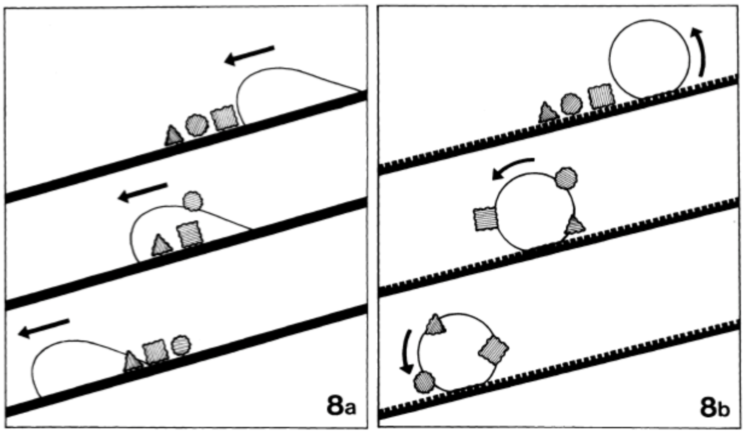


Figure 18. The self-cleaning effectiveness related to the physical surface structure with regard to (left) a smooth surface where particles are merely redistributed by water droplets, and (right) a rough surface where particles adhere to the water droplets and are removed from the surface (Barthlott and Neinhuis [3]).

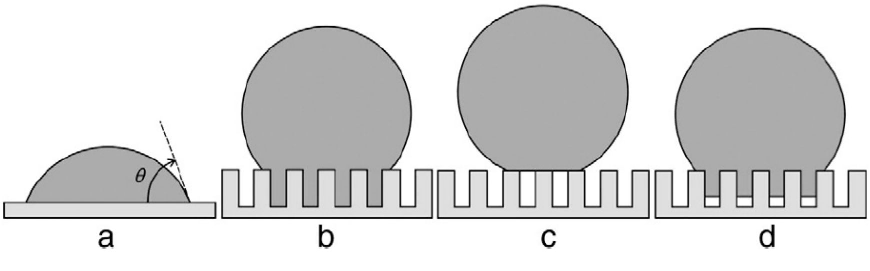
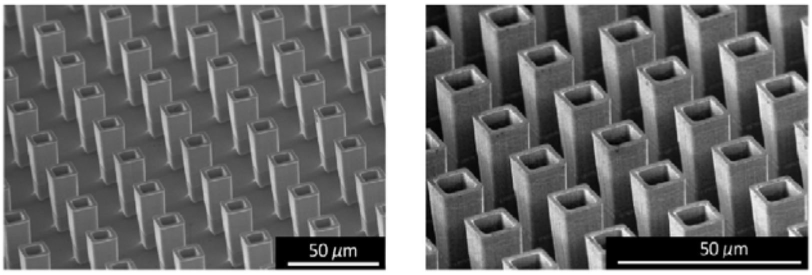
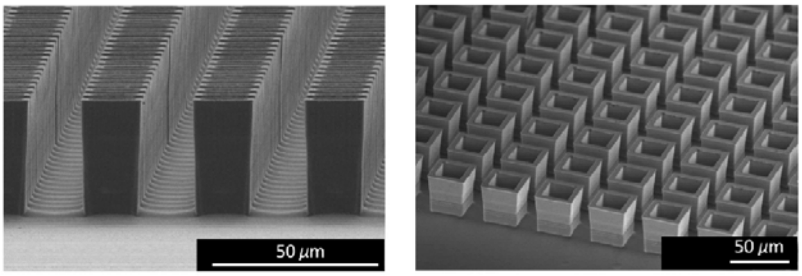


Figure 19. Illustration of wetting states of a drop sitting on a surface: (a) drop on a smooth surface (measure of the contact angle is illustrated), (b) Wenzel state, (c) Cassie-Baxter state, and (d) combined state (Antonini et al. [1]).

Several studies have fabricated various artificial coarse superhydrophobic surfaces, where some examples are shown by scanning electron microscope (SEM) images in fig.20 (Dash et al. [12]). A comparison of poly(dimethylsiloxane) (PDMS) templates and the natural lotus leaf with respect to surface morphology and hydrophobicity is given in fig.21, depicting SEM images of the surface structure of (a) the lotus leaf, (b) the superhydrophobic surface, and (c) the negative template, with droplets on the corresponding surfaces (d, e, f). Note that the lotus leaf and the superhydrophobic surface have droplets of almost the same shape, i.e. the same contact angle and hydrophobicity (Sun et al. [70]).



(a) surface 1: $a_0 = 15\ \mu\text{m}$, $\phi = 0.08$, $r_m = 2.64$ (b) surface 3: $a_0 = 13\ \mu\text{m}$, $\phi = 0.15$, $r_m = 4.47$



(c) surface 4: $a_0 = 20\ \mu\text{m}$, $\phi = 0.19$, $r_m = 3.88$ (d) surface 5: $a_0 = 27\ \mu\text{m}$, $\phi = 0.23$, $r_m = 3.55$

Figure 20. SEM images of four representative hollow hybrid superhydrophobic surfaces fabricated (Dash et al. [12]).

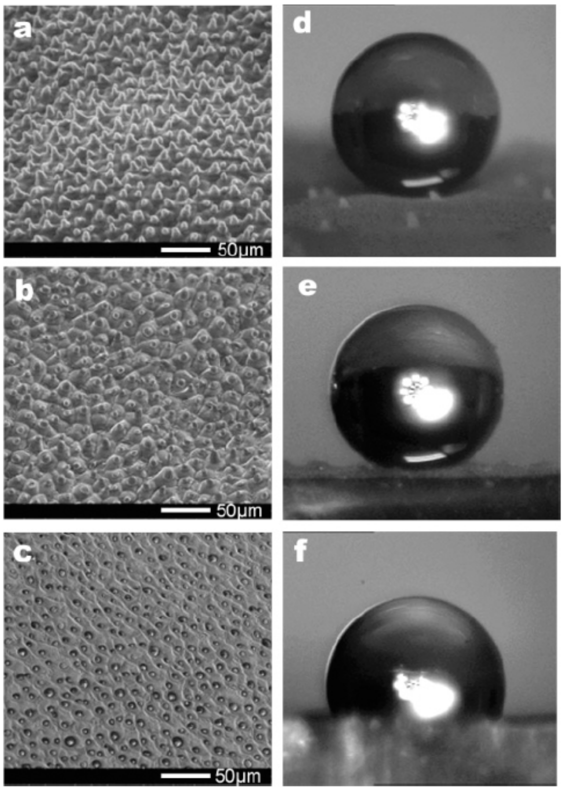


Figure 21. Comparison of PDMS templates and the natural lotus leaf with respect to surface morphology and hydrophobicity. SEM images of the surface structure of (a) the lotus leaf, (b) the superhydrophobic surface, and (c) the negative template, with droplets on the corresponding surfaces (d, e, f) (Sun et al. [70]).

The possibilities of the lotus leaf (and others) with its hydrophobicity and artificial counterparts are investigated in several studies (e.g. Barthlott and Neinhuis [3], Bhushan and Jung [5], Cheng and Rodak [10], Cheng et al. [11], Guo et al. [25], Hsu and Sigmund [27], Hsu et al. [28], Neinhuis and Barthlott [57], Sun et al. [70], Victor and Erb [75], Yan et al. [79]), whereas superhydrophobicity, links to the nanostructure of the matter and related areas are furthermore the topic of yet several more studies (Bravo et al. [6], Erbil et al. [15], Hao et al. [26], Krupenkin et al. [40], Kulinich and Farzaneh [42], Lau et al. [47], Manakasettharn et al. [49], Momen and Farzaneh [56], Qian and Shen [62], Shirtcliffe et al. [66], Soolaman and Yu [69], Teshima et al. [71], Wang and Luo [77]). Figure 22 shows examples of micromorphologies for water-repellent leaf surfaces (Hsu et al. [28]). The large collection of water-repellent and self-cleaning plant surfaces with corresponding contact angles by Neinhuis and Barthlott [57] should be noted.

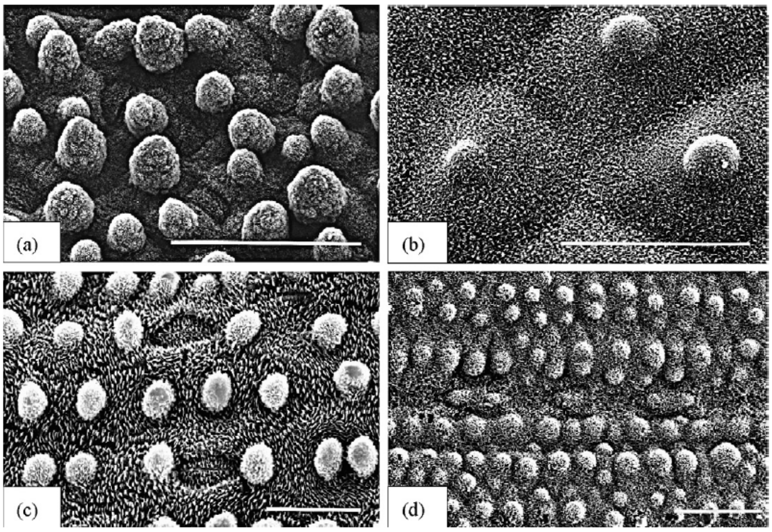


Figure 22. Examples of micromorphologies for water-repellent leaf surfaces. Water repellent leaf surfaces of (a) Nelumbo nucifera and (b) Lupinuspolyphyllos (bars = 50 µm), and (c) Gladioluswatsonioides and (d) Sinarundinaria nitida (bars = 20 µm) (Hsu et al. [28]).

As an endnote concerning the self-cleaning effect, it should be noted that the task of preventing snow and ice formation involves other crucial aspects than merely removal of dirt from these surfaces. The freezing of water below 0°C represents a huge obstacle or challenge in this respect, which in some cases is further complicated by the possible ice or frost formation above 0°C air temperature due to thermal infrared radiation loss to a cold sky and thus possible lowering the actual surface temperature below 0°C.

3.9. Investigating Icephobicity

As an extension from the self-cleaning research paths, several of the same principles may be applied for anti-icing investigations, and so far in particular superhydrophobicity and structured surface coarseness effects, e.g. the term icephobicity is introduced and is in common usage.

Several studies investigate and treat aspects concerning superhydrophobicity and related topics with various ice formation issues, see e.g. the works by Antonini et al. [1], Cao et al. [8], Eldada [14], Farhadi et al. [17], Farzaneh and Ryerson [18], Jafari et al. [29], Kim et al. [39], Kulinich and Farzaneh [43], Li et al. [48], Meuler et al. [51], Mishchenko et al. [54], Parent and Ilinca [59], Petrenko et al. [60], Ross and Usher [63-64], Ross [65], Tin et al. [72], Varanasi et al. [74], Wang et al. [76], Xiao and Chaudhuri [78], Yang et al. [80] and Zheng et al. [81].

Wang et al. [76] studied the effects of a nano-fluorocarbon coating on icing, which is depicted in fig.23. Sequential high-speed video images of droplet impact on dry and frosted superhydrophobic surfaces are shown in fig.24 (Varanasi et al. [74]), demonstrating that frost alters the wetting properties of the surface. Anti-icing coating design cases with various roughness scales are illustrated in fig.25 (Xiao and Chaudhuri [78]). Schematics for modeling of droplet freezing on superhydrophobic surfaces, using classical heterogeneous nucleation theory and analysis of dynamic wetting behavior, are given in fig.26 (Mishchenko et al. [54]), where further details are given in the figure caption.

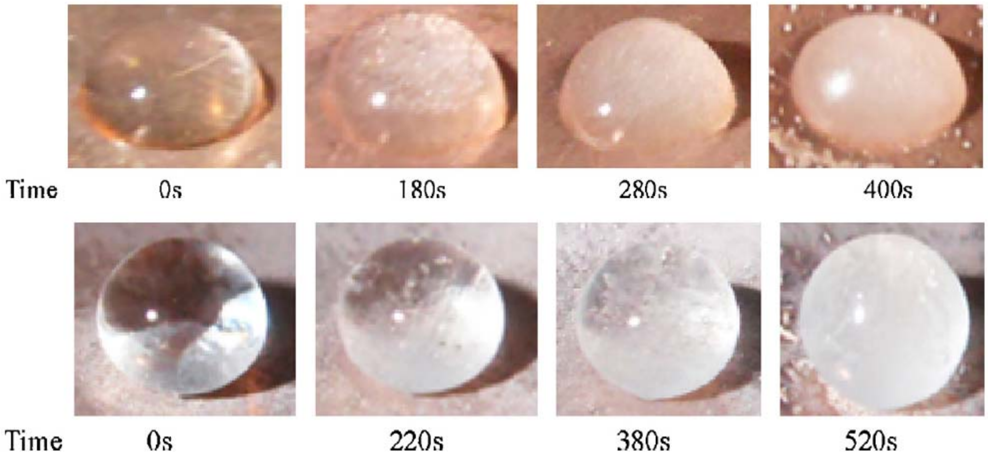


Figure 23. The icing process of a water droplet on a plain copper surface (top) and a coated surface (bottom) (Wang et al. [76]).

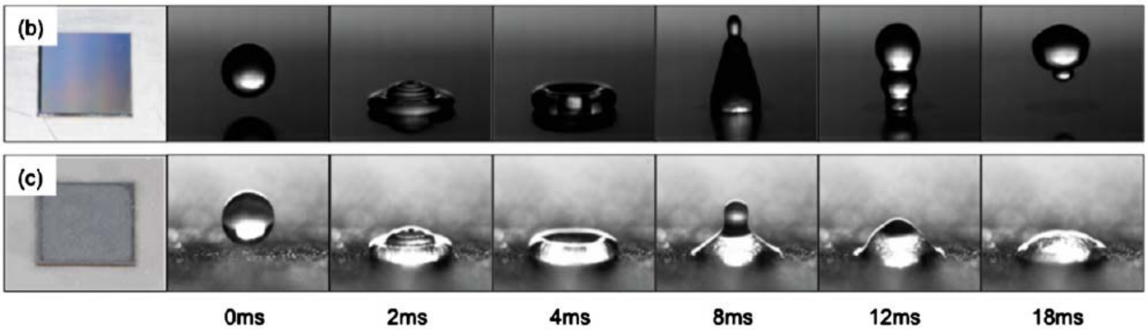


Figure 24. Sequential high-speed video images of droplet impact on dry and frosted superhydrophobic surfaces using droplets of 1 mm radius impacting the surface at velocity ~0.7 m/s. (b) Dry surface, as expected, droplet recoils from the surface, as the antiwetting capillary pressure is greater than the dynamic wetting pressures. (c) Frosted surface, frost alters the wetting properties of the surface, making the surface hydrophilic, causing Cassie-to-Wenzel wetting transition of the impacting drop, subsequent pinning and formation of ”Wenzel” ice on the surface (Varanasi et al. [74]).

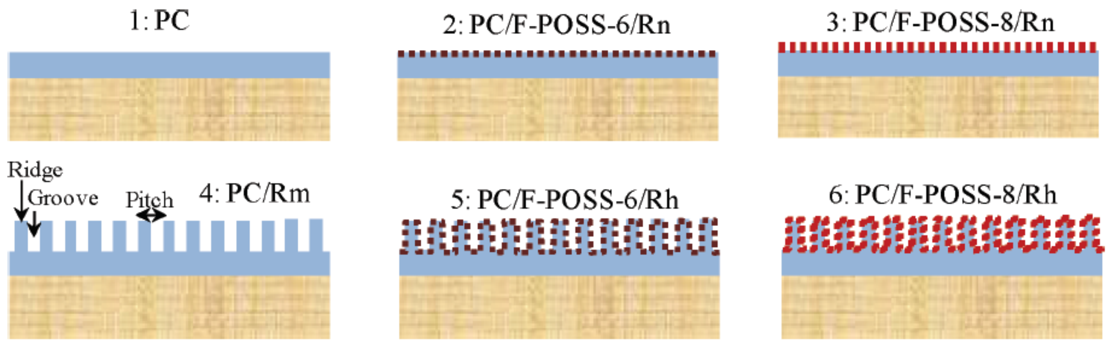


Figure 25. Anti-icing coating design cases. Rn with nanoscale roughness, Rm with microscale roughness, and Rh with hierarchical roughness (Xiao and Chaudhuri [78]).

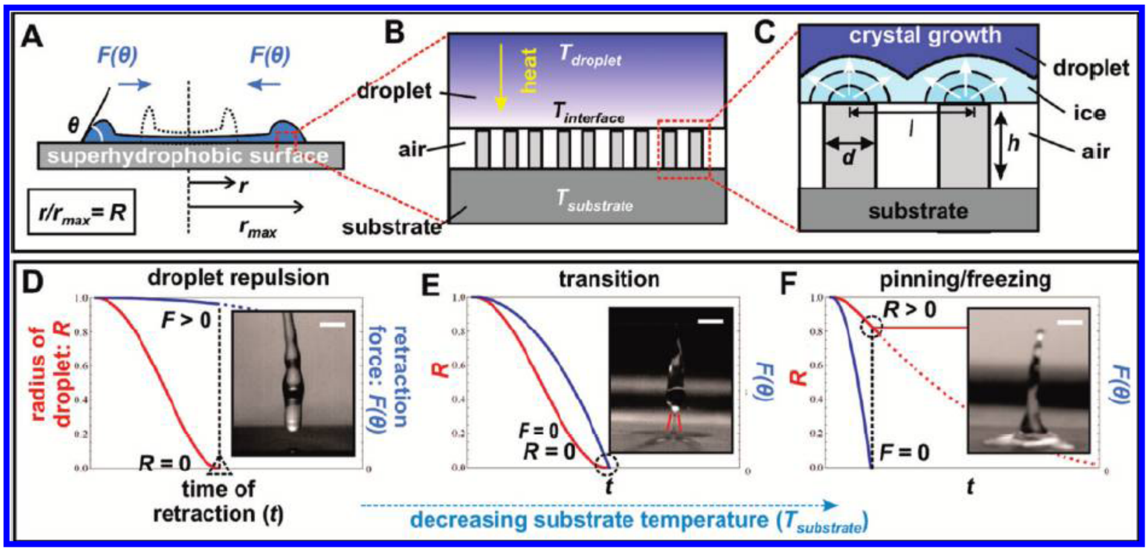


Figure 26. Modeling of droplet freezing on superhydrophobic surfaces using classical heterogeneous nucleation theory and analysis of dynamic wetting behavior. (A) Schematic of a retracting droplet. The retraction force F(θ) pulling the droplet toward the center originates from surface tension and depends on receding contact angle θ. (B) Schematic showing heat transfer from the droplet to the colder substrate, through the nanostructures and the air gaps. (C) Schematic showing hemispherical ice caps nucleated on the post tips, which reduce the dynamic contact angle. (D-F) Plots of the theoretical normalized radius (position) of the droplet (red), R, during contraction and the retraction force F(θ) acting on the droplet (blue) for three different substrate temperatures. The plots illustrate the model's predictive powers: if the retraction force is positive when R = 0, the droplet fully retracts and bounces off the surface completely (D); the critical pinning transition occurs when the retraction force becomes zero at the time when R = 0 (E); when the retraction force reaches zero before the droplet fully retracts, the contact line pins at that location and the droplet eventually freezes (F). Insets show the corresponding experimental images (scale bars are 2 mm). Red lines in panel E highlight the small remaining capillary bridge between the droplet and the substrate at the pinning transition (Mishchenko et al. [54]).

Theoretical and experimental investigations along these shown above and similar research paths may lead to improved self-cleaning properties and ultimately, surfaces able to remove snow downfall and avoid ice formation. The obstacles and challenges along these research paths may seem to be rather large, however, the potential payback is huge in a vast amount of application areas, like e.g. photovoltaic solar cell roofs and solar thermal panels.and walls.

3.10. The Self-Heating Material Solution

With *self-heating* it is meant a material and/or a solution which is utilizing *free* radiation to remove (e.g. melt) the snow and ice covering or starting to cover the solar cell panels. That is, the notation is somewhat analogous to the self-cleaning name employed for self-cleaning window panes. With free radiation it is meant radiation which can not or will not be utilized as part of the energy harvest of the building, e.g. energy which otherwise might have been utilized in solar cell panels or solar thermal panels. The obvious radiation categories coming first into mind are:

- Solar spectrum part, including diffuse radiation, which can not be utilized by the actual solar cells (or other solar utilizing units/systems).
- Ambient infrared thermal (heat) radiation.

Note that the snow is usually falling when there is no direct solar radiation, which has to be taken into account when attempting to utilize parts of the solar spectrum for snow, ice and frost removal.

Also note that the above might be possible for solar cell panels, but not so straightforward feasible for solar thermal panels, as the thermal panels may in principle utilize all the solar and infrared radiation.

3.11. The Force Field Solution

May we envision a force field which would repel all snow crystals already before they are hitting the solar cell surface? What kind of force field would this be, which in addition is not allowed to use any extra energy? Electric? Static or dynamic? Magnetic? Something else? How can snow crystals be repelled? May the dipolarity in water molecules be taken advantage of and utilized, even in solid state as snow and ice and not as liquid water? May this force field also be able to prevent air moisture condensation and freezing onto the solar cell panels, i.e. anti-frost formation?

3.12. Idea Generation

A simple illustration, fig.27, is presented in order to initiate people to ”dive” into the solar cell surface, or any other surface in principle, and envision how they could remove the snow from the solar cell panels.

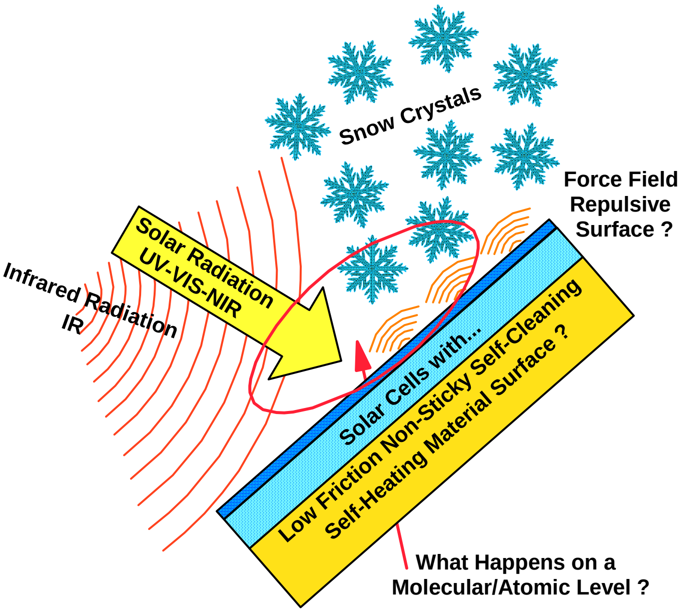


Figure 27. Illustration of a low friction non-sticky self-cleaning self-heating material surface solution, maybe with a force field, in order to generate ideas. (Illustration: SINTEF Building and Infrastructure).

3.13. The Other Solutions

The other solutions are the possible, which may even look rather impossible today, solutions which are not presented within this article. It might be a solution which will not be fruitful, but still a solution which could help in finding a fruitful solution. And it could be *the solution*. The solution which no one so far have thought about, and the solution which actually works. *Maybe you and your research team will contribute to find that solution?*

4. Further Work

Everyone reading this article is encouraged to respond to it by different means and discuss the challenge presented here at various opportunities. New ideas may be presented at various conferences and published as different popular and scientific articles. Ultimately, one may hope that a working solution will be found within a reasonable time frame. It is also crucial that the specific materials and solutions exhibit a satisfactory durability with respect to various climate exposures, thus accelerated ageing experiments in the laboratory may be beneficial to carry out (Jelle [37]).

5. Conclusions

This article addresses and investigates the challenges related to snow downfall and ice formation on photovoltaic solar cell roofs, also including solar thermal panels and walls, in order to maximize the solar energy efficiency, including a special emphasis given on possible research opportunities for the future. Various ideas and possible steps towards a solution of the challenge have been discussed, which may then in turn set in motion creative thinking and problem solving paths with new follow-up investigations. A solution within this field, i.e. avoiding snow and ice sticking to solar cell panels, may also be utilized in both similar and totally different fields, e.g. from window roofs to traffic signs which are often concealed by snow and ice. Furthermore, this work presents and elaborates the development of an experimental method for measuring friction between snow/ice and various roofing surfaces. Experimental studies of the friction between snow/ice and various roofing surfaces have been carried out, including a slip angle and a friction coefficient classification system for roofing types and material surfaces with respect to snow and ice.

Acknowledgements

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