

Self-Cleaning Glazing Products: A State-of-the-Art Review and Future Research Pathways

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Abstract

Self-cleaning technology is used in a variety of products today, with glazing products being the foremost area of application. However, there are several self-cleaning technologies in use and their self-cleaning efficiency may be unclear. This study aims to give a comprehensive state-of-the-art review of the self-cleaning glazing products available on the market today and investigate methods for measuring the self-cleaning effect. Various future research pathways and opportunities for the self-cleaning products of tomorrow are also explored within this study, with emphasis on solar energy application areas such as daylight, solar radiation transmission, electrochromism, building integrated photovoltaics (BIPV), solar cell glazing and solar cells in general. Self-cleaning products from several manufacturers that utilize two different self-cleaning technologies of either photocatalytic hydrophilic or hydrophobic capability are presented. The photocatalytic hydrophilic products in question are self-cleaning glazing products ready-to-use when purchased, whilst the presented hydrophobic products are coatings that must be applied to existing glazing products in order to yield a water-repellent and self-cleaning surface. It is stated that the self-cleaning action of the photocatalytic hydrophilic products is evident through 25 to 30 years, even during dry spills, and that they are able to maintain a cleaner surface than ordinary untreated float glass. However, the self-cleaning action of hydrophobic-coated products is limited by a relatively short life expectancy of about 3-4 years, and their self-cleaning performance is found to be feeble compared to ordinary untreated float glass. Nonetheless, the potential for future use of both self-cleaning technologies are apparent, with focus on alternative application areas such as solar cells, BIPV and information display devices, which indeed could benefit from utilizing the self-cleaning technology. Visions for future self-cleaning products are also discussed, which combine self-cleaning abilities with photovoltaism and electrochromism, whereupon the applicability of the self-cleaning technology may be greatly increased.

Keywords: Window; Self-cleaning; State-of-the-art; Solar radiation; Solar energy; Review; Photocatalytic; Lotus effect; Hydrophobic; Hydrophilic; Glazing; Future; Building integrated photovoltaics

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1. Introduction

Self-cleaning glazing is available as a thin-film outer layer on products as windows and doors; consequently, self-cleaning products are subjected to the ever-changing outdoor environment. Hence, knowledge of their ability to withstand dirtying and maintain a tolerable cleanliness and performance over time is of great importance. A standard scientific method to quantify the self-cleaning effect of these products would be helpful, especially when comparing various self-cleaning products, and considering the actual benefit by choosing a self-cleaning glazing product in preference to an ordinary product. Moreover, self-cleaning products require less maintenance, and are thereof both time- and money-saving in comparison with ordinary windows or doors, still there are certain characteristics of these products that may limit their use. To better understand the limitations and advantages of self-cleaning glazing products, this study examines what products are available on the market today, along with discussing their strengths and weaknesses, and outlining possible future research pathways and opportunities for self-cleaning technology.

A fully operational self-cleaning window, and large glazing structures, will be able to utilize and control much more of the solar radiation energy as no radiation is absorbed or reflected by any dirt on the glass surface, e.g. for daylight utilization, smart windows, building integrated photovoltaics (BIPV) as solar cell glazing and possible combinations of these. Hence, self-cleaning glazing products may lead to increased solar energy control and thus increased energy savings and user comfort.

The need for and the benefits from a standardized method to evaluate the performance of self-cleaning glazing products, has already been addressed through a research report initiated by several industrial parties in the European glass market [1]. This research report presented several work packages, with aims to understand; what contaminants affect the glazing products, the influences of the manufacturing process, the self-cleaning reaction phenomena at nano scale, and within that framework, present a possible measurement method as a proposal for standardization by CEN and ISO. This method is, among other factors, based on visual observations and haze measurements of contaminated self-cleaning specimens. The results of this study show that hydrophilic self-cleaning glass on average have a good self-cleaning effect. Hydrophobic glass, however, is observed and measured to have a considerably lower cleaning effect, even lower than ordinary clear float glass.

In an earlier study, performed by Chabas et al. [2] on the behaviour of self-cleaning glass in an urban atmosphere, self-cleaning glass is found to have an evident self-cleaning effect, even when it is not subjected to water. The field study showed that particulate organic matter (POM) was destroyed by a percentage of 44-48 % on the self-cleaning surface, and it was not observed any significant difference in effectiveness between glass specimens that were protected from rain and glass specimens that were not. However, the self-cleaning glasses had some remaining organic deposits, which were firmly bonded to the glass surface and were not washed off without human intervention. Moreover, another study, by Jelle et al. [3], emphasizes that some maintenance, due to fastened organic or inorganic dirt, will be necessary with self-cleaning products regardless of their self-cleaning nature, though maybe not as frequent as with ordinary windows. Consequently, the self-cleaning windows may therefore also have a possible positive environmental impact, as due to less cleaning the use of chemical cleaners is reduced accordingly, which otherwise might have been spilled into the ground.

The objective of this study is to attain a clear overview of the self-cleaning glazing products available today, to investigate methods for measuring the self-cleaning effect, and to explore various future research pathways and opportunities for the self-cleaning glazing products of tomorrow. To comply with these purposes, this study is divided into three parts. The first part suggests and investigates possible methods for measuring the cleaning effect of self-cleaning glazing products. The second part is a state-of-the-art review of all the large self-cleaning glazing manufacturers and their available products of today. The third and last part is a possibility study of the research and development being performed on the subject as of now, in addition to illustrate possible solutions and products for the future. The products in question in this study are mainly glass components and applications to such, e.g. windows and window treatment products. Nonetheless, the potential for self-cleaning surfaces in general, including ice and snow free surfaces, is huge. Therefore this study also encompasses various wall and roof surfaces, photovoltaic solar cells, solar thermal panels, cars, road signs, etc.

The presentation of the self-cleaning glazing products in the second part of this study includes a lot of information, like manufacturers, product names and various material properties, such as visible transmittance (T_{vis}), solar transmittance (T_{sol}), ultra violet (UV) transmittance (T_{uv}), solar reflectance (R_{sol}) and solar factor (SF), among others. The definitions and further details of these values may be found in Jelle and Gustavsen [4]. Furthermore, this study introduces a new performance term regarding self-cleaning glazing products, a self-cleaning factor (SCF), which is defined as a quantifiable measure of the self-cleaning efficiency.

In order to present all the information mentioned above, several tables are summarizing all this data, which for the most part is given in the main text. However, a more detailed tabulated description is given in the appendices. Several of the presented product properties are very important, even crucial, to evaluate and compare the self-cleaning glazing products. However, few manufacturers provide this kind of data, even though consumers and professionals need this information in order to consider and evaluate the use of the self-cleaning glazing products. Regardless of available information, the mentioned key product properties are given in the tables nonetheless, thus lacking data is seen as open spaces in the tables within this study. Hopefully, by addressing this fact, manufacturers may take initiative and provide the necessary information at their websites and other information channels. Moreover, information on the self-cleaning factor (SCF) is not given. The SCF is included in the tables nonetheless, as this factor is regarded as a valuable measure to quantify the factual self-cleaning effect of the products in question, and in effect of being mentioned, also being an incentive for future use by others.

2. Theory behind the self-cleaning effect of glazing products

As the name suggests, a self-cleaning glazing is capable of cleaning its own surface. This effect can be achieved through photocatalytic reactions within a titanium dioxide (TiO_2) thin film coating. However, the thin-film must be activated to be operational. The activation occurs by virtue of UV radiation, where the TiO_2 reacts with the oxygen and water molecules in the air and produces free radicals leading to oxidative species [1]. This process needs some daylight exposure, usually about one week, to ensure full activation. When dirt, dust and other deposits later may fasten to the surface as a result of natural weathering, the UV radiation causes oxidative species that results in photogenerated electrons and holes. Electrons will then reduce oxygen to water (vapor) and holes will oxidize the organic matter, and thereof deteriorating the dirt and dust [1,5]. Since UV radiation is abundant even on cloudy days or in shaded areas, this process is in operation non-stop during daytime.

Thereafter, the glazing product will have to remove the broken-down deposits, in order to attain the desired self-cleaning effect. This process depends upon the wettability of the surface, which is characterized as either hydrophilic or hydrophobic. When it rains and water hits a hydrophilic self-cleaning surface, the water forms thin sheets on top the glass surface that is able to wash off broken-down organic matter in one movement. If the self-cleaning surface is hydrophobic, the water forms water beads on top of the glass surface, in which the deposits are trapped and carried off the surface [5,6]. A photocatalytic process is visualized for a hydrophilic self-cleaning glass in Figure 1.

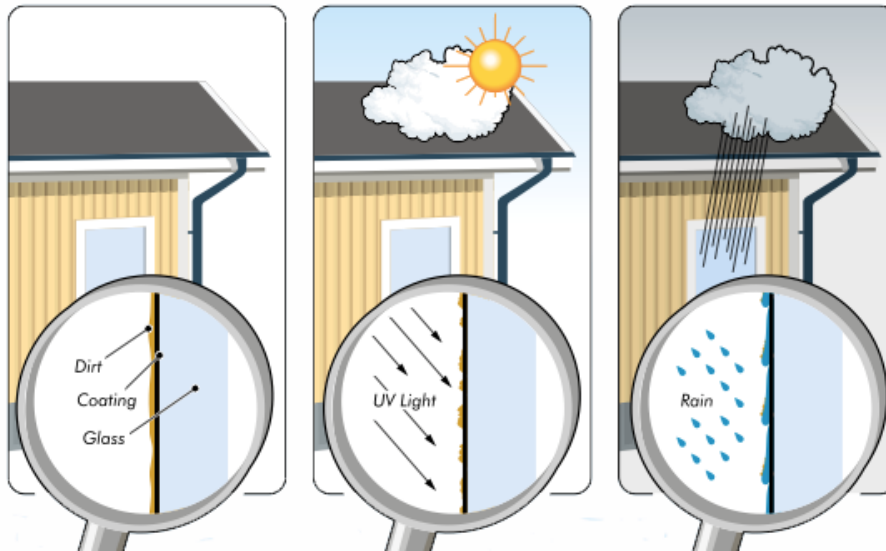


Figure 1: Illustration of how self-cleaning glass works, in three steps, from left to right: 1) activation of the coating by UV radiation and natural dirtying, 2) decomposition of the organic dirt, and 3) rain water washes away the loosened and degraded dirt. Source: Pilkington Active [6]

There are also glazing products covered by this study that does not obtain and maintain a clean surface by photocatalytic reactions, but only by altering the surface structure. Even though a glass surface may seem smooth, it is in fact microscopically pitted and pocked, and thereof disposed to attraction and embedment of dirt, dust and bacteria. However, by applying a coating that chemically reacts with the silica-based glass, causing an ultra-thin film to form on top of the glass surface, it transforms the natural hydrophilic surface of regular glass into a hydrophobic and water-repelling surface [7].

The hydrophobic and water-repellent thin-film leaves few points of attachment for possible contamination, and those contaminants that do stick to the surface, are easily removed by washing or when it rains. The pitted and uneven glass surface, along with a silicone protective and hydrophobic coating layer and the hydrophobic behavior of water, are shown in Figure 2.

The self-cleaning property of the hydrophobic surface, arise from the water contact angle with the glass surface. The water droplets on a hydrophobic surface, has a large contact angle with the surface due to the smooth surface. As a result from this, the surface tension is increased, and the water droplets are able to attract the contaminants and trap them inside their interior. A visual comparison between different glass surfaces regarding contact angles is given in Figure 3. A typical contact angle on a hydrophobic glass surface can be measured at 104° , whilst the contact angle on a hydrophilic surface is defined to be less than 90° [8].

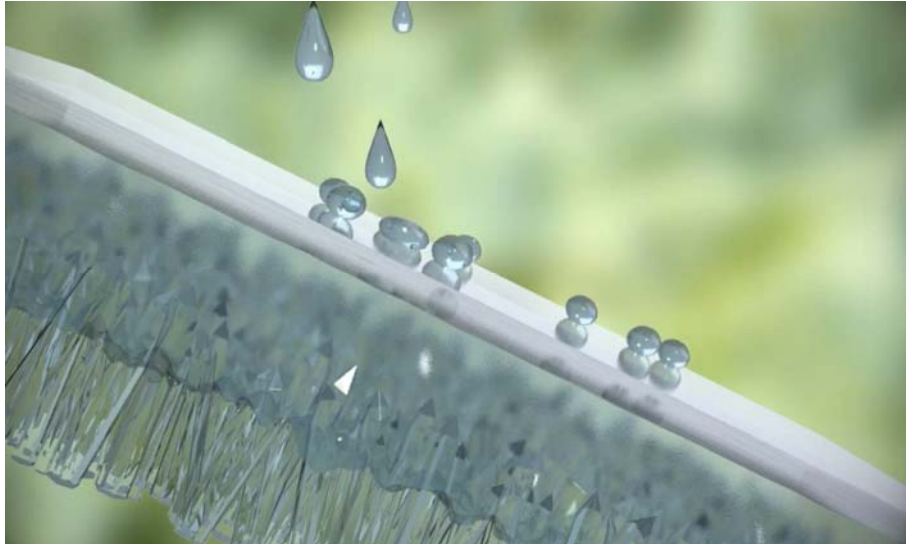


Figure 2: A microscopic view of a normally pitted and rough glass surface underneath a protective and hydrophobic BalcoNano coating. Note that this figure is not to scale. Source: Balcony Systems Solutions [7]



Figure 3: Illustration of a typical physical form of a water droplet on untreated, hydrophobic, specially-cleaned and hydrophilic glass. The contact angle is at maximum for a hydrophobic surface and at minimum for a hydrophilic surface, with untreated and specially-cleaned in between. Source: Redrawn illustration from figure by Ritec International [8]

Several investigations have been carried out on hydrophilic and hydrophobic surfaces with their respective superhydrophilic and superhydrophobic counterparts or enhancements, and on self-cleaning properties and various possible application areas in general [1,2,5,10,11,12,22,24,25,27,33,34,35,36,37,38,39,40,41,42,43,44,45,46]. It is not within the scope of this work to go into details of all these, as the focus of this work is on self-cleaning characterization methods, state-of-the-art self-cleaning glazing products of today and future research pathways for self-cleaning glazing products of tomorrow. Nevertheless, some issues and details will be treated where appropriate in the forthcoming sections, and naturally, several research paths will be using the state-of-the-art knowledge and technologies of today as foundation and stepping-stones for looking into the future possibilities of self-cleaning glazing.

Besides being able to maintain a clean and shiny surface, some self-cleaning glazing products do also have anti-microbial abilities. The surface coating or layer is able to affect the presence of bacteria, fungi and other microorganisms, as an effect of the repelling and self-cleaning properties of the glazing product. Figure 4 illustrates this connection, where few organisms appear to adhere to the self-cleaning glass, as apposed to normal float glass, where organisms seems to adhere in a much greater extent. When washed, one can also see the difference in effectiveness between the normal and self-cleaning glass.

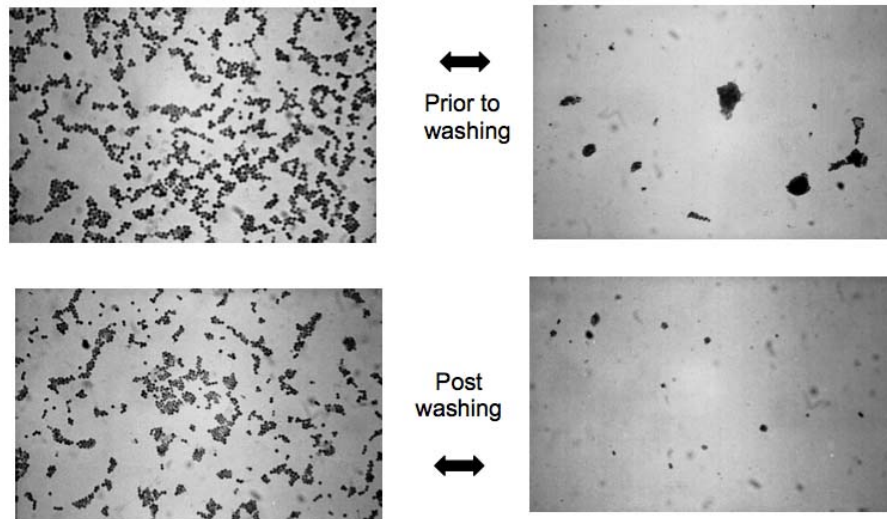


Figure 4: Micrographs of organism cells adhering to glass slides of ordinary glass (left) and self-cleaning glass (right), both before and after natural washing. Few organisms seem to fasten to the self-cleaning glass, and when washed, even less still adhere due to the self-cleaning surface. Source: Bacteria Test by Ritec International (2006) [29]

3. Methods to quantify the self-cleaning effect

Self-cleaning glazing products of today are, seemingly, often advertised to guarantee a substantial reduction in cleaning time, to eliminate the need for chemical cleaners and to maintain a natural glass shine and a clear glass surface for longer than ordinary glazing products (e.g. [7] and [9]). However, this marketing does not give the consumer any specific information on how well their product will perform over time, e.g. in terms of a quantifiable measure of the cleaning effect, i.e. a self-cleaning factor.

A method to quantify the cleaning effect of self-cleaning glazing products will not only inform users of the products cleaning performance, but also represent an easily comparable characteristic property. Presently, there are several ways to measure the amount of contamination of a surface, and by extension, a level of cleanness, e.g. by x-ray photoelectron spectrometer (XPS) and scanning electron microscopy (SEM). These apparatuses may then be used to measure chemical elements on the surface of the self-cleaning films [5,10,11].

As mentioned introductorily, there is also an existing method present, which ranks the cleanness of self-cleaning glazing products. The method uses haze measurements in order to calculate a cleaning effect value, but a description of what exactly the haze measurements entails, is not given in the research report [1,12]. However, assuming that this haze definition is similar to that of e.g. Chabas et al. [2], it is henceforth defined as the percentual ratio between diffused transmitted light and direct transmitted light. The self-cleaning effect, as introduced by Keranen et al. [1,12], can then be defined as:

$$\% \text{Cleaning Effect} = 100 (H_{\text{cycle2dirt}} - H_{\text{final}}) / (H_{\text{cycle2dirt}} - H_{\text{original}}) \quad (1)$$

where H_{original} is haze after the test specimen is sprayed with a soiling solution and dried, $H_{\text{cycle2dirt}}$ is haze after the test specimen is illuminated by UV radiation, sprayed with clean water and dried, H_{final} is haze after the test specimen is sprayed with a second soiling solution

and dried, where the measurements are carried out in the order described. Nonetheless, the higher the cleaning effect, the cleaner the glass surface will be when exposed outdoors.

The cleaning effect stated in Equation 1 seems to give well-correlated results with visual observations [1], and may thereof be recognized as an adequate method to quantify the self-cleaning effect. However, the above-mentioned method does have some drawbacks. To execute the test methods one needs somewhat specialized and expensive laboratory equipment, and an advanced level of technological knowledge and know-how to operate them [2]. It might be an idea to employ a method that is usable to others than high-skilled professionals, with equipment that is rather affordable and as easy-to-use in the field as in the laboratory. Thus is a self-cleaning factor, henceforth denoted as SCF, proposed and defined as:

$$SCF_m = (m_{rem} / m_{tot}) 100 \% \quad (2)$$

where SCF_m represents a self-cleaning factor of mass (m), m_{rem} is total mass of dirt removed by the self-cleaning glazing and m_{tot} is the total mass of dirt deposited on the self-cleaning glazing. Thus, the SCF_m -measure yields an expression of percentage; the higher the percentage, the lesser amount of dirt remains, and by extension, the cleaner the glass surface.

However, to measure the exact amount of dirt removed and deposited might be difficult, as test specimens as a whole would have to be weighed precisely both before and after dirt contamination. Another challenge might be the resolution and accuracy of the measurement apparatus when considering large specimens. Another option is to weigh the dirt itself, which calls for removing all the contaminants from the glass surface, either with spraying the specimen with a highly soluble liquid or scraping off all dirt and dust. Either way, one would have to handle the specimens with care, as the self-cleaning surface is vulnerable to mechanical strain and scratches.

Based on the abovementioned challenges, another SCF might be more applicable, one that utilizes, say, change in transparency of the specimen to quantify the products self-cleaning performance. Such an approach might be easier to execute in terms of needed equipment and mechanical knowhow. To measure a SCF on the basis of change in transparency, one could; firstly, subject the outside surface of a pristine self-cleaning glazing product to a light source. The light from this source, transmitted through the glazing, would then power a solar cell on the other side of the specimen, whereas the electrical current thereof is measured with a voltmeter. Secondly, the same exact procedure would be repeated for a “dirty” self-cleaning specimen of the same make, which have had sufficient time to self-clean beforehand. Seeing that the transparency will be reduced for a dirty specimen, the fraction of the different voltage outputs from the solar cell will constitute a percentual measure of cleanness, like Equation 1. A definition of this measurement of transparency as a self-cleaning factor is:

$$SCF_u = (U_{dust, clean} / U_{dust, ref}) 100 \% \quad (3)$$

where SCF_u represents a self-cleaning factor of voltage (U), $U_{dust, clean}$ is defined as voltage output after the test specimen has undergone dirtying and had time to self-clean, whereas $U_{dust, ref}$ is defined as the voltage output before the test specimen has undergone dirtying, as a pristine reference. However, despite the easy execution and straightforward measuring, this SCF-approach is in need of some considerations and precautions, like the measurement of mass in Equation 2.

The two measurements to be executed in Equation 3 must be performed under the same conditions, such as luminous intensity of surrounding light, to avoid unintentional influence of the solar cell voltage output. In a laboratory this is of no concern, as the measurements would take place in a darkened room. Or one could, more or less, comply with this premise by utilizing a light source far superior to the surrounding light, with regard to luminous intensity, when executing the measurements. The influence on the voltage from the surrounding light should then be negligible in comparison. However, regardless of mentioned execution method, the entire light spectrum from the measurement lamp should be transmitted through the test specimen, and not escape into the surroundings. Only then will the transmitted light from the test specimen solely power the solar cell and the voltage output be completely dependent on the cleanliness of the specimen surface.

Field tests of the self-cleaning effect on in-situ specimens might also be of interest, in case of testing the self-cleaning effect over time, and in doing so, eliminate the need to disassemble the specimen from the building construction, and with that reduce the risk of damaging the self-cleaning coating on the specimen. However, field tests require a somewhat different measurement approach than laboratory tests. To perform measurements in the field without disturbing factors such as changing solar conditions, one could do the testing during nighttime, as the only light source to power the solar cell on the inside would be the measurement lamp on the outside, more or less. If not, an apparatus that is attached on the outside of the test specimen, which block out all solar radiation and only allow the measurement lamp to transmit light through the specimen and power the solar cell on the inside of the specimen. Furthermore, the test room in which the solar cell is placed should be darkened.

If one follows the mentioned considerations and precautions when evaluating the self-cleaning factor in accordance with either Equation 2 or 3, the results should give a good indication on the self-cleaning effect of the test specimens, within the measurement accuracy. However, it is important to notice that SCF_m and SCF_u will not yield equal results. This is due to the Beer-Lambert law, which states that there is a logarithmic dependence between the transmission of radiation through a substance and the product of the distance that the radiation travels through a substance and the absorption coefficient of that substance. Moreover, the transmission of radiation is also dependent on the ratio between the incoming and outgoing radiational intensity of the substance surface in question. The relationship between the traveled distance of radiation and the transmittance of radiation may thereof be defined as:

$$I = I_0 \exp(-\alpha x) \Rightarrow T = (I / I_0) = \exp(-\alpha x) \quad (4)$$

where I and I_0 are defined as the incident and transmitted radiation intensity, respectively, α is the absorption coefficient of the substance, x is the traveled distance of the radiation, whereas T represents the transmittance of radiation through the substance. Consequently, the transmittance of light through a dirty self-cleaning glazing product will decrease exponentially with increasing thickness of the deposit layer. That is, the self-cleaning factor SCF_u (Equation 3) will be exponentially dependent on the dirt amount, whereas the self-cleaning factor SCF_m (Equation 2) will be linearly dependent on the dirt amount. Therefore, the self-cleaning factor will not be equal for Equation 2 and 3, even if the deposits on the test specimens are identical, with respect to deposit type (organic and inorganic), density and absorption coefficient. However, this is a challenge that could be addressed in-depth in future research studies.

4. Self-cleaning glazing products of today

Self-cleaning glazing products in this study are divided into two categories, according to their manner of operation, namely, factory-finished and user-finished products. The former involve all factory produced glazing products, e.g. windows and doors, on which a self-cleaning surface already is operational when purchased. The latter, 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. Note that this study does not aim to list and describe all available self-cleaning glazing products on the market, but to entail manufacturers and products that, to the authors' knowledge, are most widely used.

Key information about the different factory- and user-finished self-cleaning glazing products are presented in Table 1 and Table 2 in following sections, and in greater detail in Appendix A and Appendix B. However, data regarding performance, such as e.g. transmittance and U_g -values, is information not available for all products, as mentioned introductorily. Regardless of this, the performance designations, including the SCF, are given in the tables for illustration and demand purposes nonetheless.

4.1. Factory-finished self-cleaning glazing products

In this study, products from eight different manufacturers of self-cleaning factory-finished glazing products have been reviewed, and all of them utilizes photocatalytic reactions in order to achieve the self-cleaning effect. Moreover, the self-cleaning property is available either in a stand-alone glass product, or as a characteristic that can be combined with other glass product qualities, such as low-emissivity and high-performance insulation, i.e. tailor making a window or glazing product.

4.1.1. General overview of the factory-finished products

Information on the factory-finished products is given in Table 1. Self-cleaning products that combine the self-cleaning property with other distinctive glass product qualities are displayed with their respective product names. Some manufacturers offer different versions of their self-cleaning product, and their respective product names are also displayed in Table 1.

Table 1: Data for factory-finished self-cleaning glazing products. For further information see Appendix A

| Manufacturer | Product | Description | T_{vis} | T_{sol} | SCF |
|------------------------------------------------------------------|-------------------------------------------------|-----------------------------------------------------------------------------------------------------------|-----------|-----------|-----|
| Cardinal Glass Industries USA www.cardinalcorp.com | Neat Glass with 1" triple pane LoE-180 | Factory produced glass panes with self-cleaning coating E.g. :LoE/clear/:LoE Argon filling | 70 | | |
| Fuyao Glass Industry Group Co Ltd China www.fuyaogroup.com | Self-cleaning glass | Factory produced glass panes with self-cleaning coating | | | |

| Manufacturer | Product | Description | T _{vis} | T _{sol} | SCF |
|-------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|------------------|------------------|-----|
| Pilkington Group Ltd United Kingdom www.pilkington.com pilkington@respond.uk.com | Active CLEAR™ / BLUE™ / NEUTRAL™ | Factory produced windows – frame with 2 or 3 panes and self-cleaning coating. E.g. :4/16/:4/16/:4 Argon filling | 67 | | |
| PPG Residential Glass USA www.ppg.com herman.marini@allfacilities.com | SunClean™ | Factory produced glass panes with self-cleaning coating | | | |
| Press Glass SA Poland www.pressglass.eu nowawies@pressglass.eu | Active™ with Top-Glas Eco Plus | Factory produced glass panes with self-cleaning coating E.g. :4/16/:4/16/:4 Argon filling | | | |
| Reflex Glass United Kingdom www.reflexglass.co.uk sales@reflexglass.co.uk | RE-FLEX / RE-FLEX+ with Clear glass | Factory produced glass panes with self-cleaning coating E.g. Argon filling | 65 | | |
| Saint Gobain Glass UK Ltd United Kingdom www.saint-gobain-glass.com glassinfo.uk@saint-gobain-glass.com | SGG BIOCLEAN™ with SGG PLANITHERM TOTAL+™ | Factory produced windows – frame with 2 or 3 panes and self-cleaning coating. E.g. :4/16/:4 Argon filling | 77 | | |
| Viridian Australia www.viridianglass.com | Renew™ with Viridian Thermotech™ Clear | Factory produced windows – frame with 1 or 2 panes and self-cleaning coating. E.g. :6.38/12/:6 Argon filling | 70 | 55 | |

More detailed contact information and other key performance factors are given in Appendix A. However, not many of the manufacturers give more information on their products performance than those already displayed in Table 1.

4.1.2. Presentation and description of the factory-finished products

The self-cleaning glazing products produced by the manufacturers listed in Table 1 are described further underneath, with emphasis on how the product works, its characteristics, what maintenance is required by the manufacturer and possible product limitations, etc. Note that this information for the most part is collected from material made public by the various manufacturers themselves.

Cardinal Glass Industries – Neat Glass

Neat Glass is a self-cleaning glass pane, but the Neat technology can also be combined with all other glass products from Cardinal Glass, such as the low-emission glass, LoE. The self-cleaning technology of Neat Glass entails a titanium dioxide layer that reacts with UV-rays,

thereby causing organic deposits on the glass surface to decompose. It is also added a thin layer of silicone dioxide to the Neat Glass, making the glass surface very hydrophilic and smooth. When it rains, or when the glass is washed, the decomposed organic dirt and dust are easily removed. The “water-sheets” that form on the hydrophilic surface, easily run off and evaporate quickly, greatly reducing water spotting.

Another quality of the Neat Glass is the high visible transmittance. Because of the sputtering process used in production of Neat Glass, more visible light is allowed through the glass, also causing less reflectance. Visible transmittance (T_{vis}) and exterior visible reflectance are allegedly 90 % and 8 %, respectively, when Neat Glass is combined with a normal clear float single pane glass. However, for the 1” triple pane LoE alternative given in Table 1, the same performance factors are quite different; 70 % and 20 %, respectively.

As most self-cleaning glazing products, Neat Glass also need occasional maintenance to maintain a clean and spotless surface over time. Moreover, Cardinal Glass only produces glass panes, meaning that a separate window manufacturer is needed to fit the panes into frames. However, Neat Glass is only suitable for exterior use in façades, roofs and conservatories, seeing that UV radiation is required for the self-cleaning action to be operational [13].

Fuyao Glass Industry Group – Self-cleaning Glass

The Self-cleaning Glass from Fuyao Glass utilizes a high temperature, pyrolytic spraying process to create a thin-film self-cleaning surface on clear float glass, which function as an anti-mold and anti-fungi surface, besides being self-cleaning. The capability to self-clean is made possible by photocatalytic reactions on the surface thin-film, which degrade organic deposits when exposed to UV radiation. When it rains or the surface is cleaned, as the hydrophilic properties of the coating causes the water to form large “sheets” and wash away the broken down organic deposits as well as loose inorganic matter, in accordance with Figure 1. Furthermore, the self-cleaning coating can also be applied to float glass in combination with other glass qualities, such as fire protection, noise and high-performance insulation capabilities, resulting in multi-purpose glass units.

By the manufacturer it is promised a permanent photocatalytic action, even under weak UV radiation, e.g. during nighttime and on cloudy days. Moreover, the self-cleaning coating is advertised to last in excess of 15 years, or as long as the glazing itself under normal conditions. The self-cleaning coating itself does not affect the light transmittance of the under-laying glass. The light reflectance, however, may be somewhat altered; where a low visible light reflectance of 10 % is promised. Furthermore, the haze value is allegedly below 0.8 %, which should indicate an effective self-cleaning coating, however, further information must be given in order to conclude. Nonetheless, the self-cleaning coating needs occasional manual cleaning to prevent build-up of contaminants, inorganic materials in particular, and to ensure further effectiveness of the photocatalytic reactions [14].

Pilkington Group Limited – Active Clear/Blue/Neutral

Pilkington Active is a self-cleaning coating that can be factory applied to most Pilkington glass products in insulation glass units, to provide benefits such as thermal insulation, solar control, noise reduction and fire protection. The combination of the self-cleaning coating and solar control glass is branded either Active Blue or Active Neutral, where the difference is their tint; blue and neutral color, respectively. Active Clear is the original Pilkington self-cleaning glass, without any additional benefits and with a neutral tint. Pilkington Active is a

hydrophilic coating on which the self-cleaning property is due to the photocatalytic reactions of a titanium dioxide thin-film surface – once exposed to UV radiation, the coating breaks down any organic deposits, and causes rainwater to “sheet” down the glass and wash away the loosened organic and inorganic dirt and dust.

The self-cleaning coating does not affect the glass in terms of strength, but it somewhat reduces the light and energy transmitted through the glass by about 5 %. For certain viewing angles it also has a slightly greater reflectance than normal glass. The self-cleaning coating is developed to last as long as the glass unit itself, and as it is integral to the glass, and therefore permanent, it will not peel, break, fade or discolor with time. However, silicone or silicone-based products may compromise the effectiveness of the self-cleaning coating, so silicone sealants or gaskets should be used with care.

Seeing that Pilkington Active utilizes photocatalytic reactions in order to achieve a self-cleaning effect, it needs an activation period to be fully operational; around 5-7 days of solar radiation exposure is enough, as illustrated by Figure 1. Consequently, Pilkington Active is only suitable for external use. If there are heavy dirt deposits on the surface, the solar radiation may not penetrate the dirt layer and reach the coating, it might then be necessary to wash off the surface by hand and let the surface reactivate itself for a few days to be fully operational again [6].

PPG Residential Glass – SunClean

The SunClean self-cleaning coating can be used in conjunction with solar control glass, in order to achieve a high energy efficiency and other benefits in addition to the self-cleaning property. The SunClean coating is a durable and transparent coating of titanium dioxide that is factory applied to hot PPG glass panes during the formation process, creating a strong and long-lasting bond between the coating and the glass. This process makes the coating an integral part of the outer surface and yields a durable photocatalytic and hydrophilic surface, which is easy to clean, dries quickly and causes minimal spotting and streaking.

The SunClean is dependent upon UV radiation, as any other photocatalytic surface, in order to function correctly, and is therefore only used externally. The energy within the UV radiation is able to disintegrate organic dirt and dust, however, the coating is not able to loosen inorganic deposits, such as sand or paint and cement runoff. Occasional cleaning and maintenance is necessary, also in periods with little or no rain to wash away loosened deposits. Still, the sheeting-action of water on the glass surface enables quick cleaning with minimal effort.

Moreover, seeing that the SunClean self-cleaning coating is integral to the glass, it does not degrade or discolor with time, due to normal tear and wear. However, one should be careful with the use of abrasive cleaning solutions since these can potentially damage the glass surface. Nonetheless, when undamaged, the SunClean coating reduces the UV radiation transmittance with 40 %, protecting the interior from UV degrading, and improves the solar heat gain coefficient (solar factor) by 5 % compared to normal glass [15].

Press Glass SA – Active

The Active self-cleaning glass uses a titanium dioxide coating to achieve the photocatalytic reactions as depicted in Figure 1. It enables the glass surface to degrade organic dirt and dust, and when it rains, easily wash them off. Unfortunately, more information on the workings and limitations of this product is not given from Press Glass SA on their public website. One would have to contact them directly to acquire more details [16].

Reflex Glass – Reflex/Reflex+

The products from Reflex Glass promote two main features; solar protection and easy cleaning. The latter property is achieved through use of a polymeric hydrophobic coating on the outer glass surface, which is permanently bonded to the glass surface during the factory production process. The difference between the two glass products, Reflex and Reflex+, is the magnitude of their main properties; where the latter has the highest reflection of IR and UV radiation, offers a lower U-value and external reflection. The Reflex+ unit does also have a conspicuous azure tint. These products are suitable for external use only, because of their functional dependency of UV radiation.

On account of the factory application method, the hydrophobic polymer coating is permanently bonded to the glass surface, and is designed to last 10 years. It is not damaged, nor is its properties affected by silicone or certain cleaning agents, and it repels water that traps dirt and runs off the surface with ease. However, the manufacturer does not give any information on the possibilities of regaining or renewing the easy-clean property after the promised 10 years operating time. Though, it is promised that the coating does reduce the cleaning time with as much as 70 %, and does also protect against mold and algae growth as well as embedment of dirt and dust, as illustrated in Figure 4 [17].

Saint-Gobain Glass UK Limited – Bioclean

The Bioclean self-cleaning quality can be incorporated into most Saint-Gobain products, and may thereof yield additional benefits other than self-cleaning, e.g. solar control or fire protection. The self-cleaning coating is a transparent layer of mineral material that holds photocatalytic and hydrophilic properties, and is fused into the glass itself. This process makes the coating very durable, and is designed to last as long as the window itself.

As most photocatalytic coatings, the Bioclean product needs UV radiation to activate itself, normally around 1 to 4 weeks, and to maintain the self-cleaning property. This radiation breaks down organic dirt that lands on the surface and prevents inorganic deposits from fastening to it. When it rains, the hydrophilic surface causes the water to “sheet” and spread out across the glass, thus rinsing the broken down dirt away and drying quickly and uniformly. During dry spills, it may be necessary to wash the glass manually using a hose, etc. As UV radiation is required for operation of the self-cleaning coating, the Bioclean product is suitable for external use only.

To ensure optimal self-cleaning performance, however, the window should be installed at a minimum angle of 10° to the horizontal, so that water will run off easily. In addition, the coating performance is vulnerable to silicone products, e.g. sealants, sprays, suckers and gloves, and abrasive or water-repellent cleaners, as these products may form an outer film on the surface or scratch it, and therefore prevent or affect the hydrophilic action of the glass.

On account of the special production process and integration of the self-cleaning coating with the glass pane, it does neither influence the mechanical and acoustic nor the thermal properties of the glass. Moreover, the coating does not have any characteristic tint or reflective surface – it looks just like normal glass [9].

Viridian – Renew

Renew is a self-cleaning glass quality that can be incorporated with virtually any Viridian solar or thermal control glass, e.g. ThermoTech. The Renew coating is a thin, clear and pyrolytic titanium oxide film that is fused onto the glass surface. This fusion process makes the

self-cleaning coating an integral and permanent part of the glass, and is therefore very durable. In addition, the Renew product is highly transparent with virtually identical properties to clear float glass.

The Renew titanium oxide coating utilizes UV radiation in order to degrade organic deposits on the glass surface, as any other photocatalytic products, as seen in Figure 1. The titanium oxide film acts as a catalyst, activated by UV radiation, to break down dirt and dust into vapor and carbon dioxide gas, whilst the hydrophilic property of the surface causes rain water to sheet out across the glass and remove loosened organic and inorganic deposits. However, in periods with little or no rain and considerable exposure to inorganic dirt, such as salt and sand, or even large amounts of organic deposits that may take a substantial amount of time to break down, it is necessary to clean the glass manually.

It is not given any information by the manufacturer on guaranteed operating time for the self-cleaning action, however, due to the factory fusion process, it is assumed to be as long as the window itself. As with most glazing products, it is advised to install the Renew glass at a minimum angle of 10° to the horizontal, to ensure quick water runoff. Moreover, seeing that the Renew coating requires UV radiation to uphold the self-cleaning effect, it is not suited for inside use, only in exterior façades, roofs or conservatories [18].

4.2. User-finished self-cleaning glazing products

At the time of writing, there are a handful of manufacturers that specializes in offering easy-to-use professional or do-it-yourself (DIY) user-finished products. They are either in form of a bottled liquid, to be applied with a cloth to a glass surface or any vitreous surface such as ceramic tiles and porcelain, or as pre-treated sachets to process the surface with.

4.2.1. General overview of the user-finished products

The three manufacturers covered by this study, their basic contact information, product brand names and some key product information are given in Table 2. One manufacturer offers two different versions of their self-cleaning product. Both alternatives are displayed in Table 2.

Table 2: Data for user-finished self-cleaning glazing products. For further information see Appendix B

| Manufacturer | Product | Description | T_{vis} | T_{sol} | SCF |
|-----------------------------------------------------------------------------------------------------------|-------------------------------|---------------------------------------------------------------------------------|-----------|-----------|-----|
| Balcony Systems Solutions Ltd United Kingdom www.balconano.com enquiries@balconette.co.uk | BalcoNano™ | Professional and DIY applicator, wet wipes with BalcoNano coating (DIY Sachets) | | | |
| Rain Racer Developments United Kingdom www.rainracer.com sales@rainracer.com | Rain Racer™ | DIY applicator, liquid polymer | | | |
| Ritec International Ltd United Kingdom www.ritec.co.uk info@ritec.co.uk | ClearShield™/ ClearVision™ | Professional and DIY applicator, polymeric resin and factory produced windows | | | |

None of the products in Table 2 are provided with information regarding the transparency, due to the nature of the appliance of the products (e.g. variations in thickness of the applied product may occur). As these products are only a supplement applied to a glass surface and not a glass product itself, the transparency or other material properties like R_{sol} and SF (as given in Appendix B), are not natural characteristics to be given. One could suspect that self-cleaning glazing products could somehow affect the material properties of glass, however, according to the manufacturers they do not [7,8,19].

4.2.2. Presentation and description of the user-finished products

As given in Table 2, there are three manufacturers of user-finished self-cleaning products covered by this study, all of them located inside the United Kingdom. In the following, their products are described and their characteristics discussed and explained. Note that this information for the most part is collected from material made public by the various manufacturers themselves.

Balcony Systems Solutions – BalcoNano

BalcoNano is, as described by the manufacturer, a transparent and protective thin film that can be applied to any silica-based surface. There are two application methods for this product, as a DIY-kit, in form of sachets containing a cleaner and a coating wet-wipe towelette that can be applied to already installed glass, or as a professional batch method, in which a glass unit is subjected to a vapor deposition system in an air tight chamber. The latter is suitable for higher volumes for industrial applications, whereas the former is intended for the consumer market.

The BalcoNano coating covers the uneven glass surface, as depicted in Figure 2, and hence embedment of dirt, dust and bacteria is reduced. A chemical reaction between the glass (silica) surface and the coating causes an ultra-thin silicone film to form on top of the glass surface, and turns the regular glass surface into a hydrophobic and water-repelling surface. Furthermore, through a simple neutralization process, the chemicals used in the coating and their by-products become chemically inert shortly after application, and are thereof of no danger to the environment.

By using the BalcoNano product, it is promised that the glass will stay clean for longer and ensure easier cleaning when it is necessary. Because, although the product is advertised as self-cleaning, cleaning is still needed, as earlier studies have claimed [3]. The dirt and dust that is attached to the glass only require water to wash off, thus no harsh cleaning chemicals or detergents are necessary, or applicable for that matter. The use of heavy cleaners may remove the protective coating. Due to less cleaning, the manufacturer promises a reduction in maintenance costs of at least 50 % and up to as much as 90 %, and with a life expectancy of 3-10 years. However, coating duration is greatly dependent on the manner of application and maintenance performed. Still, none of these promised values are scientifically verified, or at least further proven by the manufacturer and made available to the consumer [7].

Rain Racer Developments – Rain Racer

Rain Racer is a protective polymer coating that is stain resistant and light scratch resistant, due to its lubricity. It is sold as a DIY-kit, consisting of a bottled liquid coating and a gel cleaner, intended for the ordinary consumer and professionals alike. It can easily be applied to already installed glass windows and doors, or be factory-applied by professionals.

The polymer coating is simply wiped on to the glass surface with a dry cotton cloth etc., and when applied, the coating creates a hydrophobic surface within minutes. The manner of operation derives from the principle shown in Figure 2, i.e. the coating evens out the glass surface and prevents contaminants from embedding into the glass surface. Due to this characteristic, Rain Racer is advertised, besides being self-cleaning, as having anti-microbial properties. Due to the smooth finish of the polymer coating, bacteria and fungi have considerable less surface sites to attach themselves to. And in case the bacteria and fungi do adhere to the glass, they easily get trapped inside the water beads due to surface tension when raining or cleaning, and thus roll off the glass.

Rain Racer Developments promises a life expectancy of 3-4 years for exterior windows and doors, depending on the environmental strain, maintenance and method of appliance. A factory (professional) fitting usually offers longer life expectancy than a DIY-fitting. The polymer coating does require some occasional maintenance, but does not chip, peel or discolor with sunlight, neither is it claimed to be damaged by ordinary chemical cleaners and detergents [19].

Ritec International – ClearShield/ClearVision

ClearShield is a polymeric resin that is applicable to all vitreous surfaces, like glass, porcelain and ceramics. It can be applied to these surfaces through two application methods; through the ClearShield System, intended for the commercial/industrial market, where factory produced glass is sprayed with the polymeric resin, and as a retail DIY-kit. The latter is marketed as ClearVision, and is applied to regular glass windows and doors with ordinary cleaning-wipes etc.

When the polymeric resin is applied to ordinary glass, it cross-links to form a strong chemical bond that will protect the glass surface and transform it into a smooth and hydrophobic surface, as illustrated in Figure 2. It is promised that the polymeric resin will not affect the transparency in any way, that it is chemically inert (at least to most substances), non-hazardous and UV-stable. As it is firmly bonded to the glass surface, it will not crack, peel or flake. Moreover, glass treated with the polymeric resin, either applied through the ClearShield System or the ClearVision DIY-kit, also attains an effective protection against adhesion and growth of microorganisms, as shown in principle earlier in Figure 4.

The manufacturer Ritec International does not guarantee a minimum service life, but generally promises a clarity and visibility like new with an easy-clean surface for years. However, this is based on that an after-care program, consisting of specially formulated cleaners, is performed regularly. Furthermore, this self-cleaning product does require some cleaning, but on average, the cleaning time intervals and the cleaning time in specific, are reduced to less than half of that for ordinary glass. Still, it is important to notice, that abrasive cleaners and harsh chemicals will attack the ClearShield-surface, and deteriorate its performance [8].

5. Self-cleaning products of tomorrow

In order to develop better self-cleaning products, it is interesting to reflect on the products of today and to identify their possibilities for improvement. Moreover, many of the self-cleaning glazing products covered by this study, hold characteristics that are interesting for applications and products other than glass windows and doors. Combining the self-cleaning effect of a hydrophilic or hydrophobic surface with other products, on which a clean surface

has an impact on its performance, would be of great use. Opportunities with applying self-cleaning technology in combination with other building elements, and in combination with products from other fields of interest are also discussed in the following.

5.1. Reflections considering the self-cleaning glazing products of today

The self-cleaning glass study by Keranen (2007) mentioned introductorily [1], 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. The hydrophobic glass surfaces were even found much less clean than ordinary clear float glass, as illustrated in Figure 5.

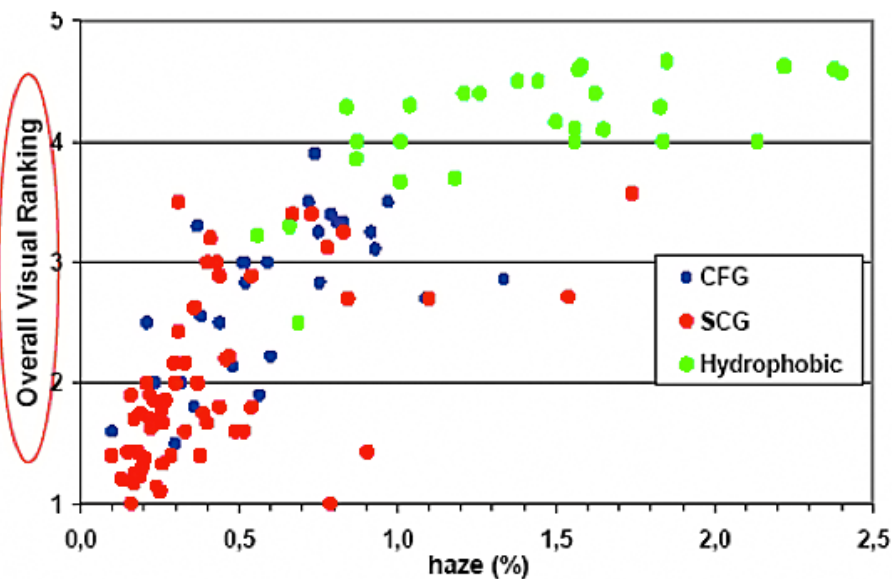


Figure 5: Haze value versus overall visual ranking for clear float glass (CFG), self-cleaning glass (SCG, hydrophilic photocatalytic glass) and hydrophobic coated glass, where the haze value is defined as the ratio diffused/direct transmitted light through the specimen, and the overall visual ranking is defined as perceived cleanliness of the glass surface, ranked from 1 (very clean) to 5 (very dirty). Source: Keranen et al. (2007) [1]

The unsatisfactory performance results by hydrophobic glass presented in Figure 5, might be explained by the results found in another study, by Fürstner et al. (2005) [11]. This work investigates the self-cleaning properties of artificial superhydrophobic surfaces. Several specimens were tested, among them replicates of different superhydrophobic plant surfaces (e.g. Lotus plant) and some smooth hydrophobic surfaces, all constructed of the same polymer. During testing the specimens were subjected to artificial contamination, and later rinsed by virtue of artificial fog and rain in order to examine the self-cleaning effect. During testing it became evident that the amount of contaminant remaining on the specimen surface after rain treatment, depends on the kinetic energy of the drops hitting the specimen surface, hence dependent upon the impact pressure. The relationship between the impact pressure and the remainder of contaminant for two of the artificial superhydrophobic surfaces and one smooth hydrophobic surface is illustrated in Figure 6.

The results in Figure 6 are rather conclusive; the replicas of superhydrophobic plant surfaces were cleaned quite well with rain, and the remainder of contaminant is evidently reduced with increasing impact pressure. However, the smooth hydrophobic surface was nearly unaffected

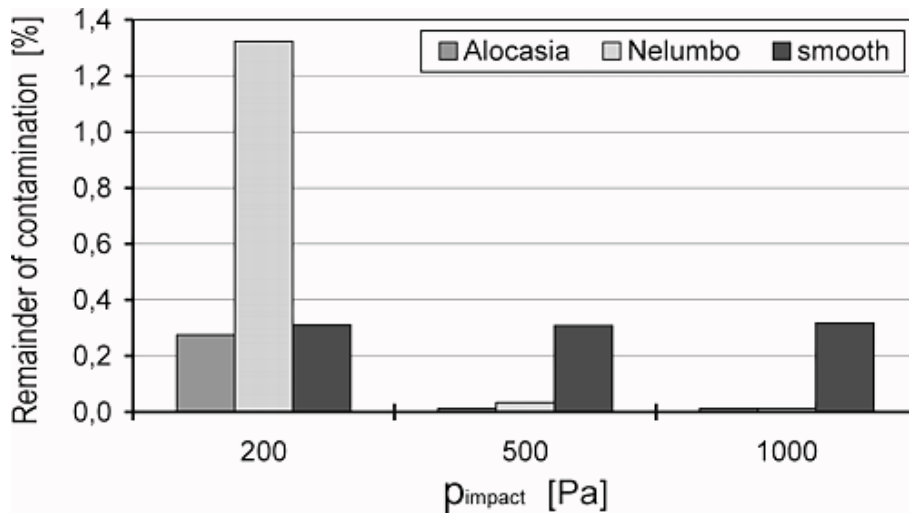


Figure 6: Remainder of contamination on replicates of two plant superhydrophobic surfaces and one smooth hydrophobic surface after sprinkling with water, versus varying impact pressure of the water droplets. Source: Fürstner et al. (2005) [11]

by the impact pressure, and thereof demonstrates the limited ability of smooth hydrophobic surfaces to be decontaminated by drop impact only [11]. Seeing that the glass specimens in the study by Fürstner et al. are installed vertically, as most glass windows and doors are, the hydrophobic glass, especially, are dependent upon lashing rain to effectuate their self-cleaning property. Thus, in the event of absent lashing rain, the self-cleaning effect will be accordingly. Moreover, it is noteworthy that building windows might even be sheltered from lashing rain by the virtue of overhanging rafts and cornices.

However, the effect of lashing rain with regard to photocatalytic surfaces is not as apparent as with smooth hydrophobic surfaces, due to the degrading of organic matter on the TiO_2 -surface. This statement is supported by the results from Chabas et al. (2008), where it was observed that the self-cleaning action on TiO_2 -surfaces took place, even in absence of rain [2].

In elucidation of the abovementioned, the self-cleaning performance comparison between photocatalytic hydrophilic TiO_2 -coated glass and hydrophobic polymer coated glass in Figure 5 seems reasonable. However, the self-cleaning performance advantage of ordinary clear float glass over smooth hydrophobic glass in Figure 5 remains to be explained. Nonetheless, it appears as if hydrophobic glass requires regular manual cleaning to decontaminate the surface and prevent accumulation of dirt and dust, thus could more appropriately be defined as an easy-to-clean product rather than a self-cleaning product.

As described earlier, the user-finished self-cleaning glazing products in question in this study have a lifespan of about 3-10 years, depending on the manner of application, maintenance and environmental conditions. However, the durability of user-finished products exposed to harsh weather and high levels of pollution, e.g. in northern coastal city areas, would most likely be in the lower end of the mentioned lifespan scale, regardless of the product application method. Because of the mechanical strain caused by frequent cleaning, which should be necessary at least according to the results from Figure 5 and Figure 6, and the possible degrading property of pollution, the manner of application would probably only be of secondary importance. In order to maintain a self-cleaning, or easy-to-clean, surface, one would therefore have to reapply the hydrophobic coating every 3 years or so. By comparison, the photocatalytic factory-finished self-cleaning glazing products are advertised with a self-cleaning property lifespan equal to the window itself, e.g. 25-30 years.

The advertised maintenance costs and time reduction when using hydrophobic glazing products would most likely vanish when considering necessary reapplying of hydrophobic resin. Nonetheless, the hydrophobic user-finished self-cleaning glazing products still do exhibit several advantages over ordinary untreated glass, leaving the mentioned unexplained self-cleaning advantage of ordinary clear float glass out of account. The antibacterial property and easy-to-clean and smooth surface are still desirable. However, considering the mentioned disadvantages in self-cleaning effect and durability when exposed outdoors compared to photocatalytic factory-finished products, it might be more appropriate to utilize the hydrophobic user-finished product technology on indoor application areas, e.g. inner doors, mirrors, balcony and staircase glass or on the interior side of a window.

Photocatalytic factory-finished self-cleaning glazing products might seem superior to the hydrophobic user-finished glazing products, still there are considerations to allow for and limitations to be aware of when utilizing the photocatalytic products. Silicone have been mentioned to alter the hydrophilic property of the TiO_2 -surface, and by extension, reduce the self-cleaning effectiveness, therefore special care must be taken when using e.g. gaskets and groove-products in whole-glass-frames, which must be silicone free. Moreover, many photocatalytic factory-finished products requires special cleaning agents when cleaning the glass surface, in order to prevent deterioration of the surface hydrophilic thin film.

In addition, the photocatalytic titanium dioxide thin film only manages to disintegrate organic matter on the glass surface, not inorganic. Therefore, deposits such as salts or sand require water to be removed, thus coastal areas, where salt build-up is a known problem, might not be ideal for this glazing product. However, somewhat more frequent cleaning will probably solve this challenge. Finally, even though these factory-finished glazing products are advertised as self-cleaning, they do need some occasional rinsing to maintain a clear and clean surface [3].

5.2. Possibilities for extended use of self-cleaning technologies

As self-cleaning technology already are being combined with e.g. anti-reflection and low-emissivity coatings on windows, which make up multifunctional products [3], one could believe that applying the technology from self-cleaning products onto, say, smart windows, building integrated photovoltaics (BIPV) or solar cells in general, would be possible and probably have a considerable positive effect too.

Building integrated photovoltaics are considered a very promising renewable energy technology, mainly because of its dual action nature, as a BIPV system serves as a building envelope material and power generator simultaneously. Examples of BIPV systems are given in Figure 7. The technology may not only reduce the building material costs and photovoltaics mounting costs, but also arrange for reduced building energy costs as a result of using the photovoltaic system [20]. These are all desirable effects of utilizing BIPV, however, if the use of this technology becomes widespread, in the sense of actual implementation in a single construction project and in the construction industry in general, time-consuming and expensive maintenance (to remove accumulated dirt from the surface) is inevitable in order to uphold a tolerable photovoltaic effect.

The greater the exposed surface area of photovoltaics, the greater the area on which dirt and dust are able to deposit, and thus affect the effectiveness of the photovoltaics, such as the solar cell effectiveness. Seeing that solar cells are subjected to the environment just as exterior windows are, deposits are able to adhere to the solar cell surface, which naturally will influence the solar cell efficiency. As the theoretical efficiency limit for, say, traditional



Figure 7: Illustrations of available BIPV systems, from left to right; curved clay-looking tiles and transparent halo ceiling. Source, respectively: Solar Thermal Magazine (2010) [30] and Global Energy Network Institute (2009) [31]

crystalline silicon solar cell devices is around 33.7 % [21], which is rather low, one should aspire to utilize every percent up to that limit. When it is also known that many thin film silicon solar cells employ sheets of glass as surrounding protection, it is neither difficult to see the possibility of using a self-cleaning coating or glass product, nor the positive effect of its application.

Therefore, if self-cleaning technology were to be implemented onto a solar cell surface of a BIPV system, extensive maintenance is avoided and the solar cell efficiency is upheld. However, this is assuming that the self-cleaning glazing products used do not negatively affect the solar transmittance and hence the solar cell efficiency. Furthermore, if the self-cleaning BIPV system were to be developed into and sold in the shape of traditional building elements, such as the curved clay-looking solar tiles and the transparent halo ceiling illustrated in Figure 7, the system would probably be even more favorable to the consumers. Smart windows such as electrochromic glazing [32], could also benefit from utilizing a self-cleaning technology. Seeing that the lesser dirt to adhere to the smart-window surface, the better the smart window performance and its user comfort would be.

Another possible area of application for the self-cleaning technology is information display-devices, such as traffic signs, sign posts, billboards and license plates among others. These devices are constantly being exposed to environmental effects such as pollution, road salt and dust. Sooner or later the legibility of the displayed information will be compromised, whereas the legibility of safety information, e.g. in the field of road traffic, is of particular importance to uphold in order to avoid misunderstandings and possible hazardous situations. When taking into account the number of display-devices in use throughout the road network, the time and money needed for cleaning are considerable [22]. A self-cleaning surface would therefore be greatly valued.

Extended use of self-cleaning coatings as to being able to protect against or limit the presence and growth of bacteria, fungi and other microorganisms would be of great interest (see e.g. the earlier presented Figure 5 [29]). In that respect, the recent discovery of some very young scientists, Ando et al. [47], that Ag_2O_3 clathrate may be an effective antimicrobial agent, visualizes that discoveries and innovations might still be achieved with relatively well-known materials and inexpensive means. Thus, discoveries within this field may then ultimately turn out to be suitable for various self-cleaning applications.

Furthermore, self-cleaning surface coatings are usually applied or manufactured onto vitreous surfaces like windows and ceramics, but in recent years this has also been made possible for

more tactile surfaces like wood or concrete. Paint with added titanium dioxide crystals that induces photocatalytic properties has already been developed. However, self-cleaning performance data or information regarding its durability is unknown [23]. Nonetheless, when considering the total painted, or somehow treated, area on a construction as apposed to fenestration area, the benefits that arise from utilizing this product are easily understood. Furthermore, a self-cleaning surface might also serve as an environmental protective layer of sorts, besides being just self-cleaning, e.g. when considering wooden elements. A durable and lifelong protection against rot and fungi would without doubt be a great advantage. This mindset is also applicable to the automotive industry. For several years self-cleaning technology has been utilized in production of windshields, mirrors and other car glass [14,24]. However, the main environmental protection for the car body is still the paint, which is very vulnerable to scratches, and thereof rust, when left untreated. Therefore, a self-cleaning and scratch-resistant coating, and even self-repairing, as apposed to ordinary wax, would be of particular interest.

5.3. Possibilities for improvements of the self-cleaning technology of today

As indicated by earlier performance studies, the self-cleaning glazing products of today are in need of some improvement. In attempt to follow this petition, it is in the following listed two suggestions on possible improvements of the existing self-cleaning technology that is believed to have the greatest potential. Short descriptions of each suggestion and general ideas for further research are given. Note that the suggested ideas are derived from earlier studies, and are repeated and augmented here in order to emphasize their potential.

Pursue superhydrophobic surface characteristics

The Lotus leaf is known for its superhydrophobic properties and self-cleaning ability. In a study by Barthlott and Neinhuis (1997) [25] several plant species were tested in order to investigate important surface characteristics. It was found that the leaves from the Lotus plant *Nelumbo nucifera* have excellent water repellence abilities, hence the term “Lotus-effect”, and that it managed to uphold a very clean surface during artificial contamination. This is, for the most part, because of its wide contact angle of about 160° and distinctive physical surface structure. Therefore, it is safe to say that superhydrophobic surfaces, like the *Nelumbo nucifera*, hold great self-cleaning abilities.

The investigations by Keranen (2007) [1] indicated that the hydrophobic products in question in the study performed poorly with regard to self-cleaning. However, no information is given on the make of the tested hydrophobic products or their contact angle. Nonetheless, assuming that the contact angle is as for a typical hydrophobic glass surface, as mentioned earlier, roughly 104° [8], one might conclude that the contact angle is of great importance when measuring self-cleaning performance. Thus, it should be of interest to develop superhydrophobic surfaces to use in conjunction with self-cleaning products, rather than hydrophobic surfaces with a lesser contact angle.

Furthermore, considering the results by Fürstner et al. (2005) [11], 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 of superhydrophobic ability 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. Some other metal specimens removed close to 100 % of the contaminants, because of their pronounced sheer structural surface composition. However, these results indi-

cate that it should be possible, with the technology today, to manufacture self-cleaning superhydrophobic products, which should yield far better self-cleaning results than those presented by Keranen (2007) [1].

The possibilities of the Lotus leaf with its hydrophobicity is investigated in several studies [25,34,35,45], and superhydrophobicity (including ultrahydrophobicity [42]) is furthermore the topic of yet several more studies [11,27,34,36,37,39,40,42,43,44,46], where links to nanostructure of the matter and hence nanotechnology are given in various works

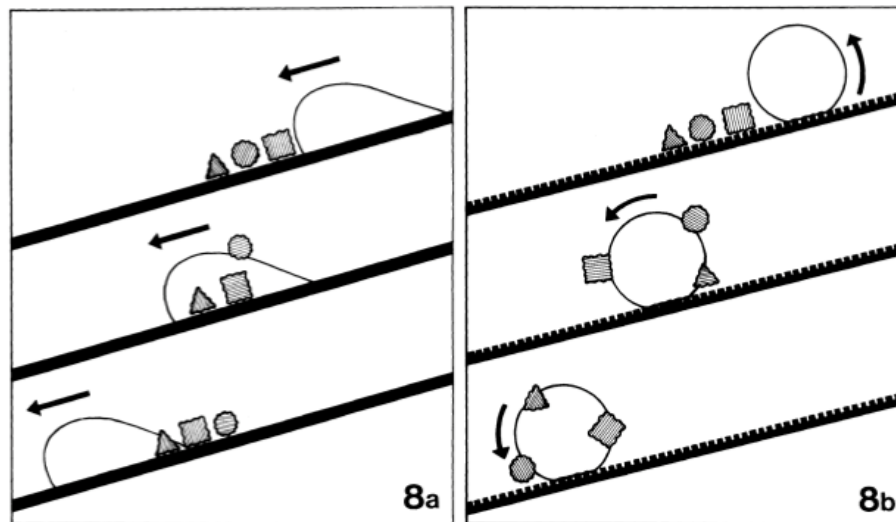


Figure 8: The relationship between the physical surface structure and the self-cleaning effectiveness, with regard to a) a smooth surface, where particles are merely redistributed by water droplets, and b) a rough surface, where particles adhere to the water droplets and are removed from the surface. Source: Barthlott and Neinhuis (1997) [25]

[1,12,33,35,40,45]. The large collection of water-repellent and self-cleaning plant surfaces with corresponding contact angles by Neinhuis and Barthlott (1997) [41] should be noted. Theoretical and experimental investigations along these and similar research paths may lead to improved self-cleaning properties and even new discoveries within various fields.

Pursue a coarse micro-structure surface

In the study by Barthlott and Neinhuis (1997) [25], the importance of the physical surface structure, besides the mere contact angle, with regard to self-cleaning ability is emphasized. It was found that water droplets on smooth surfaces, with a relative high contact angle, tend to only disperse of contaminant particles, rather than removing them from the surface. This is as opposed to fairly rough surfaces, with a high contact angle, where contaminant particles tend to adhere to the water droplets, and in effect being removed from the surface entirely. This difference in self-cleaning ability is found to be mostly because of the reduced adhesion force-ratio amid the adhesion forces between the material surface and contaminant particle versus the water droplet and contaminant particle. An illustration of the relationship between the physical surface structure and the self-cleaning effectiveness is given in Figure 8.

The self-cleaning technology that would have to be utilized for e.g. information display devices meant for road traffic or self-cleaning glazing in an urban area, must be robust and durable enough to withstand the harsh environment of highly trafficked roads and highways, and cost-effective enough to be produced at an industrial scale. A DIY hydrophobic polymer

coating will probably not satisfy these criteria, with special emphasis on durability, as mentioned earlier. However, by elucidation of the abovementioned, it is by Gerber and Tuma (2005) [22] developed several possible solutions that might satisfy the mentioned conditions.

Gerber and Tuma (2005) [22] present a self-cleaning surface structure invention and several embodiments of it that might satisfy the need for durable and cost-effective self-cleaning products. By artificially creating a material surface on which the physical exterior structure has or develops a capillary effect, after which the quotient of capillary work and adhesion work is greater than 1, the surface capillaries will have a negative rise. This means that 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. An example of a preferred embodiment of the proposed invention, which is illustrated in Figure 9, is a surface structure consisting of small geometric projections immediately adjacent to each other and mounted on the material superstructure.

When considering the course surface structure illustrated in Figure 9, one might believe it to be unfitting for products that require a very high transparency because of the fairly large projection dimensions of about 2-100 μm by 5-100 μm (width/length by height) [22]. These dimensions are larger than the average surface roughness of normal float glass, which is around 0.20 μm or below [26]. This should indicate that even if the material used is transparent, e.g. glass, a course surface structure, like the one presented by Gerber and Tuma [22], would affect the transparency of the product. However, there are developed other methods that also employs a rough surface structure in order to achieve self-cleaning properties, which in addition achieves an optical transmission of above 90 %, as for regular clear float glass [27]. Nonetheless, if the transmission is affected or not, a self-cleaning surface like the one presented in Figure 9, might be applicable to fenestration products made of e.g. aerogel, which already is in use as semi-transparent or translucent walls and façades, or other application areas that does not require complete transparency as regular glass [3,28].

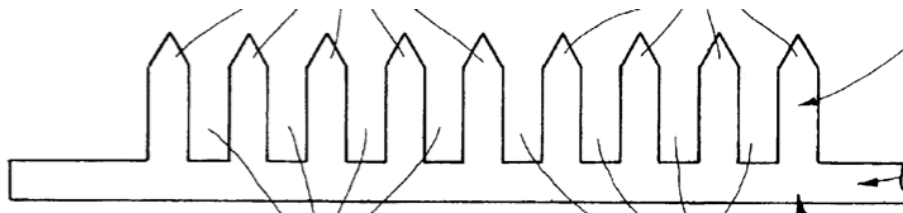


Figure 9: Microscopic view of one embodiment of the display device surface structure invention, where small geometric projections aligned adjacent to each other and mounted on top of a material superstructure. Explanatory descriptions of the workings of the projections given on the original figure are omitted here. Source: Gerber and Tuma (2005) [22]

6. Visions for future self-cleaning products

The self-cleaning technologies of today, and the products utilizing these technologies, do have some limitations. However, future research and development might disperse of these restrictions. Exposure to UV radiation is a condition for the photocatalytic self-cleaning products of today, in connection with both activation and maintenance of the photocatalytic thin film. Even so, further advances in this technology might reduce the activation time or the needed UV radiation intensity for operation, or both. Future photocatalytic products might

also be able to fully utilize the UV radiation energy, in order to degrade all organic deposits, and maybe also degrade inorganic deposits as well. An even greater vision is glazing surfaces on which natural contaminants simply do not adhere to, and with a life expectancy equal to the glazing itself. If realized, one does not need any degrading capability or any maintenance at all, in order to facilitate cleaning. That is, a genuine self-cleaning product in its very essence.

If one were to extend the idea of a true self-cleaning surface, it could also include other abilities than just self-cleaning; a nano scale coating with protective and electrical conductive abilities as well could be of profound interest. A very thin coating made of e.g. carbon or a mixture of carbon elements, e.g. graphene, could present protective abilities, e.g. large tensile and compression strength. Furthermore, electrical conductivity could be of interest especially when considering the possibility of electrochromism, which, in combination with float glass, could constitute electrochromic abilities. If one were to extend this property even further the coating could possibly also generate electricity through photovoltaism. When combining these properties with a high contact angle surface that repel any contaminants, it becomes clear that a nano-coating like this can serve many demands, thus making up a multi-functional coating. This idea is not limited to glazing products only, but can be of great use on solar cells and BIPV, or on façades and walls in general.

Furthermore, self-cleaning abilities could also be introduced into other areas than fenestration. Seeing that materials such as wood, concrete and metal all are vulnerable towards environmental influences, and may require frequent maintenance in order to function properly, a protective and self-cleaning layer could be of interest. Wood needs stain or penetration in order to be protected against fungi and rot, reinforced concrete is vulnerable to carbonization, metal is in need of paint or galvanization as a means to be protected against corrosion, whilst all three materials are vulnerable to willful plundering like graffiti. What if one could combine a protective layer or a material conversion product, such as stain or impregnation chemicals, respectively, with a self-cleaning surface coating or resin, the material surfaces would be protected against both natural aging and unwanted human vandalism. A product like this could reduce maintenance time and costs, and extend the life expectancy of the material. Considering the extensive use of these materials, the sheer value of these benefits could be immense, and the idea should on these facts alone be a future vision to pursue.

7. Conclusions

This study shows that there are many self-cleaning glazing products available on the market today, the majority of which are factory-finished. These factory-finished products are not necessarily only self-cleaning, but are also available with high-insulation properties and low-emissivity coatings, thus covering a variety of needs in one product. In addition, the photocatalytic and hydrophilic capabilities of these products makes it possible to degrade organic surface deposits by virtue of UV radiation, and when exposed to water, these sediments are easily washed away. This self-cleaning action is apparent even in the absence of rain, and is according to the manufacturers, expected to be apparent for 25-30 years. In comparison, the user-finished do-it-yourself hydrophobic self-cleaning glazing products covered in this study have a life expectancy of 3-4 years. However, if professionals apply the hydrophobic coating, its durability may be increased up to as much as 10 years. Yet, this is strongly dependent upon the environmental conditions that the coatings will be exposed to. Moreover, the hydrophobic coatings only provide a smoothed surface that makes it hard for sediments to attach, i.e. it does not degrade deposits.

According to several earlier studies, the photocatalytic hydrophilic self-cleaning glazing products appear superior to the hydrophobic. This may substantiate a conclusion in which the hydrophobic products in question better fit the description of easy-to-clean rather than self-cleaning. Furthermore, hydrophobic products may also be of greater benefit to the user if utilized indoors, seeing that photocatalytic actions does not work without UV radiation, whereas photocatalytic hydrophilic products seem to have the greatest potential for further use with outdoor glazing products. However, it is important to notice that photocatalytic hydrophilic products do need some manual cleaning as well as the hydrophobic products. Hence, the advertised environmental benefit of using these products does strongly depend upon the frequency of manual cleaning, and remains to be further examined and evaluated.

There are many research opportunities and future possibilities for both hydrophobic and photocatalytic hydrophilic self-cleaning technologies, e.g. smart windows, building integrated photovoltaics and solar cells in general are areas of application that could benefit greatly from a self-cleaning technology. Furthermore, the self-cleaning technology might also be of importance to other application areas than fenestration, seeing that self-cleaning information display devices and self-cleaning façades could significantly reduce cleaning costs and maintenance time. Moreover, the superhydrophobic capabilities and physical surface structure of the Lotus plant yield evident self-cleaning properties, which should be pursued and thus constitute a foundation for further development of the self-cleaning glazing products of today.

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Appendix A - Overview of factory-finished self-cleaning glazing products

Table A: Literature data for factory-finished self-cleaning glazing products. U_g is given in $W/(m^2K)$, whilst T_{uv} , T_{vis} , T_{sol} , R_{sol} , SF and SCF are given in %




| Manufacturer | Product | Illustration | Description | U_g | T_{uv} | T_{vis} | T_{sol} | R_{sol} | SF | SCF | Reference |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|-------|----------|-----------|-----------|-----------|----|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Cardinal Glass Industries 775 Prairie Center Dr #200 55344 Eden Prairie, MN USA Tel: +1 952 229 2600 Fax: +1 952 935 5538 www.cardinalcorp.com | Neat Glass with 1" triple pane LoE-180 |  | Factory produced glass panes with self-cleaning coating E.g. :LoE/clear/:LoE Argon filling | 0.99 | 13 | 70 | | | 56 | | http://www.cardinalcorp.com/technology/reference/loe-performance-stats/ [19-03-2012] |
| Fuyao Glass Industri Group Co Ltd Fuyao Industrial Park, Fuyao City Fujian Province, P.R. 350301 China Tel: +86-591 8538 3777 Fax: +86-591 8538 2719 www.fuyaogroup.com | Self-cleaning glass |  | Factory produced glass panes with self-cleaning coating | | | | | | | | http://www.fuyaogroup.com/en/products/deep_cleaning.html [24-04-2012] |
| Pilkington Group Ltd Alexandra Business Park, Prescot Road St Helens, Merseyside, WA10 3TT United Kingdom Tel: +44 (0)1744 28882 Fax: +44 (0)1744 692660 www.pilkington.com pilkington@respond.uk.com | Active CLEAR™/BLUE™/NEUTRAL™ |  | Factory produced windows – frame with 2 or 3 panes and self-cleaning coating. E.g. :4/16/:4/16/:4 Argon filling | 0.60 | 10 | 67 | | | 49 | | http://www.pilkingtonselfcleaningglass.co.uk/literature/default.htm [07-03-2012] |
| PPG Residential Glass PPG Industries, One PPG Place Pittsburgh, 15272 Pennsylvania USA Tel: +1 8887 7445277 www.ppg.com herman.marini@allfacilities.com | SunClean™ |  | Factory produced glass panes with self-cleaning coating | | | | | | | | http://www.ppg.com/corporate/ideascape/resglass/homeowners/product/sunclean/Pages/default.aspx [07-03-2012] |

| Manufacturer | Product | Illustration | Description | U_g | T_{uv} | T_{vis} | T_{sol} | R_{sol} | SF | SCF | Reference |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|------------------|----------|-----------|-----------|-----------|----|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Press Glass SA Nowa Wies, ul. Kopalniana 9 42-262 Poczesna Poland Tel: +48 3432 75069 Fax: +48 3432 75801 www.pressglass.eu nowawies@pressglass.eu | Active™ with Top-Glas Eco Plus |  | Factory produced glass panes with self-cleaning coating E.g. :4/16/:4/16/:4 Argon filling | 0.5 | | | | | 37 | | http://www.pressglass.eu/our-glass/advantages-of-our-solutions/ease-of-cleaning-of-the-glass-unit?lang=en [08-03-2012] |
| Reflex Glass 1 Pinfold Road, Thurmaston Leicester, LE4 8AS United Kingdom Tel: +48 0116 269 6297 Fax: +48 0116 269 6291 www.reflexglass.co.uk sales@reflexglass.co.uk | RE-FLEX / RE-FLEX+ with Clear glass |  | Factory produced glass panes with self-cleaning coating E.g. Argon filling | 1.0 ¹ | 1 | 65 | | | 35 | | http://www.reflexglass.co.uk/technical.php [19-03-2012] |
| Saint Gobain Glass UK Ltd Weeland Road, Eggborough East Riding of Yorkshire, DN14 0FD United Kingdom Tel: +44 1977 666100 Fax: +44 1977 666200 www.saint-gobain-glass.com glassinfo.uk@saint-gobain-glass.com | SGG BIOCLEAR™ with SGG PLANITHERM TOTAL+™ |  | Factory produced windows – frame with 2 or 3 panes and self-cleaning coating. E.g. :4/16/:4 Argon filling | 1.2 ¹ | 30 | 77 | | | 68 | | http://www.selfcleaningglass.com/performance.asp [07-03-2012] |
| Viridian 95 Greens Road Dandenong VIC 3175 Australia Tel: +61 1800 810403 Tel: +61 3921 22222 www.viridianglass.com | Renew™ with Viridian Thermotech™ Clear glass |  | Factory produced windows – frame with 1 or 2 panes and self-cleaning coating. E.g. :6.38/12/:6 Argon filling | 2.5 ¹ | <1 | 70 | 55 | 17 | 63 | | http://www.viridianglass.com/Products/default.aspx [08-03-2012] |

¹ The given value is assumed to be U_g , however, there is no information given through respective brochures or company web sites that confirm this, as of reference date

Appendix B - Overview of user-finished self-cleaning glazing products

Table B: Literature data for user-finished self-cleaning glazing products. U_g is given in $W/(m^2K)$, whilst T_{uv} , T_{vis} , T_{sol} , R_{sol} , SF and SCF are given in %

| Manufacturer | Product | Illustration | Description | U_g | T_{uv} | T_{vis} | T_{sol} | R_{sol} | SF | SCF | Reference |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------|-------|----------|-----------|-----------|-----------|----|-----|-----------------------------------------------------------------------------------------------------------------------------------------|
| Balcony Systems Solutions Ltd Unit 6 Systems House Eastbourne Road, Blindley Health Lingfield, Surrey, RH7 6JP United Kingdom Tel: +44 1342 410411 Fax: +44 1342 410412 enquiries@balconette.co.uk www.balconano.com | BalcoNano™ |  | Self applicant wet wipes with BalcoNano coating (DIY Sachets) | | | | | | | | http://www.balconano.com/BalcoNanoSachets.aspx [07-03-2012] |
| Rain Racer Developments PO Box 73, Waterlooville Hampshire PO7 8SY United Kingdom Tel: +44 023 9224 0824 sales@rainracer.com www.rainracer.com | Rain Racer™ |  | Self applicant liquid polymer | | | | | | | | http://www.rainracer.com/pb2/houseg.htm [07-03-2012] |
| Ritec International Ltd Innova House, Innova Science Park 4 Kinetic Crescent, Enfield, EN3 7XH United Kingdom Tel: +44 (0)2083 448210 Fax: +44 (0)2083 448211 info@ritec.co.uk www.ritec.co.uk | ClearShield™/ ClearVision™ |  | Professional applicant polymeric resin and factory produced windows | | | | | | | | http://www.ritec.co.uk/clearshield-system/why_choose [08-03-2012] |