Life cycle assessment of nanoTiO_2 coated self-cleaning float glass

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ABSTRACT

In recent years superhydrophilic and photocatalytic self-cleaning coatings have been used mainly in easy-to-clean surfaces field. Self-cleaning glasses are one of the first building nanocoating applications. These products are based on the photocatalytic property of a thin layer of TiO_2 deposited at the surface of the glass. When exposed to UVA radiation, TiO_2 reacts with the oxygen and water molecules present in the atmosphere to produce free radicals leading to oxidative species. These species are able to reduce the concentrations of airborne pollutants and organic substances deposited on the materials surface. The present study concerns the ecodesign of industrial scale up of nanoTiO_2 self-cleaning coated float glass production performed by LCA (life Cycle Assessment) methodology. This work is a part of a regional Italian project named "ARACNE". The main aim of this project is to study and ecodesign eco-friendly building materials with higher technological properties.

Keywords: life cycle assessment, self-cleaning coating, float glass, nanotitania, scale up.

1 INDRODUCTION

Titanium dioxide is one of the most important and common photocatalyst because of its outstanding efficiency (even under weak solar irradiation), compatibility with a large number of materials and good stability. With the development of TiO_2 nanomaterials, its uses ranges over a variety of fields such as functional coating photoelectrolysis, photocatalysis, dye sensitized solar cells, gas sensor, optical fibers, electrochromic material for display devices, biomedical fields, etc. [1]. In the building sector, titanium dioxide has been used traditionally as a white pigment. Nowadays, functional titanium dioxide coatings are being developed for applications in glasses, polymers, glazes, resins, metals and ceramics. Because these materials are widely used in the building sector, the well-known photocatalytic properties of TiO_2, which decomposes air pollutants as nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Moreover, since UV light also induces superhydrophilicity, TiO_2 can be applied on solid surfaces to obtain self-cleaning and antifogging features. Sol-gel process is the most frequently synthesis route used to prepare TiO_2 nanoparticles, because of its low processing cost, simplicity and ability to produce thin and uniform films on large area substrates. TiO_2 nanosuspensions can be applied directly on surfaces (glasses, mirrors, ceramics, etc.) or added to liquid media (paints, resins, glazed, etc.) and successively sprayed on substrates. There are several coating methods to create a thin film on glass surface, the mainly are: *vaccum arc deposition* [2], *reactive dc-sputtering* [3], *alkaline hydrothermal method* [4], *hydrothermal method* [5], *chemical solution method* [6], *reactive dc-sputtering* [7], *successive-ionic-layer-adsorption and-reaction (SILAR) method* [8], etc. In this work, a modified coating method consisting in first a decrease of the initial substrate roughness with acetic acid and then dip-coating of the softened glass into a TiO_2 nanosuspension has been used with the aim to produce films with enhanced adhesion to the substrate.

2 EXPERIMENTAL SECTION

Saint Gobain soda-lime float glass has been used as substrate. With the aim of increasing the adhesion of the coating and based on previous investigations made by our research group, a decrease of the surface roughness of the substrate has been carried out before the TiO_2 deposition. This has been made by soaking the glass in 96% CH_3COOH for 4h. The chemical etched glass has been coated by dip coating with 5 layers of a commercial anatase TiO_2 nanosuspension provided by Colorobbia S.p.A., using a dipping rate of 85 mm/min. Finally, the film has been dried at 110 °C for 1.5 h.

3 ECODESIGN OF AN INDUSTRIAL SCALE PROCESS

As above mentioned, the present LCA study is an accompanying study within regional Italian project named "ARACNE". The research project has optimized the method of coating of float glass thanks to experimental texts that have been carried out in a laboratory. The research continued with the intent to design the industrial scale up of the developed coating method.

The LCA analysis of the process on a laboratory scale has not been considered since, in according with Shibasaki et al. [9], the LCA results of laboratory scale do not necessarily represent the environmental burdens which would be caused after scaling up to a typical mass production. The reasons are:

- there might be changes due to scale up in process yield as well as in energy efficiency of the process. These can influence the environmental burdens, as these affects the material and energy use as well as the amount of emissions and waste.
- there might be changes in technology and for the material or energy provision affects the LCA results as well.
- in LCA analysis of pilot/laboratory plants, processes are often seen as isolated or independent of each other. The effects due to changes in plant utilization are not considered sufficiently.

In this work, starting from laboratory data, the best enviromental performance of the industrial scale up process of nanoTiO_2 self-cleaning coated float glass has been evaluated. In order to ecodesign the industrial scale process it has been necessary to consider literature data and databases included in SimaPro 7.3.3 software (e.g. Ecoinvent database has been used to model the float glass process), since the laboratory scale do not give meaningfull information about plants, equipments, internal transports, ordinary maintenance operations of equipment and machineries. In addition, because the data related to the installation operations, use phase and end of life of nanoTiO_2 self-cleaning coated float glass has not been considered in the laboratory scale process it has been necessary to study and ecodesign these aspects.

A life cycle assessment of nanoTiO_2 self-cleaning coated glass has been carried out in order to assess the most critical enviromental burdens.

4 LIFE CYCLE OF A SELF-CLEANING FLOAT GLASS

The entire life cycle of a nanoTiO_2 self-cleaning coated float glass shown in Fig.1, consists of four main steps: 1) production, 2) installation, 3) use and 4) end of life. The production step, in turn, is divided in: a) cutting, b) lapping, c) ultrasonic cleaning, d) soaking in acetic acid, e) dip coating. The present study consider the use of a self-cleaning float glass for private bulding.

As it is still unknown the potential toxicity on human health of titanium dioxide nanoparticles it should be adopted a safe behavior in all life cycle steps where workers can come into contact with or inhale nanoparticles. In particular, in nanoTiO_2 film application, glazing installation, use and end of life steps is likely to have release of nanoparticles emissions by nanocoating surface. For these reasons air filters and personal protective equipment have been included in this study. However, it has been evaluated a preliminary attempt to define the damage generated by the emissions of titania nanoparticles during the above mentioned phases.

The main steps of the life cycle of nanoTiO_2 self-cleaning coated float glass are described below.

4.1 Production

a) First of all the Saint Gobain soda-lime float glass is cut in customer required size,
b) the obtained glass are then polished to bevel the edges and corners,
c) ultrasonic cleaning is a process that is able to clean the glass surface through the use of ultrasound and acetone as solvent media,
d) the clean glass is soaked in 96% CH_3COOH for 4h, in order to decrease the surface roughness of the substrate,
e) finally, attacked the glass is coated with 5 layers of a nanoTiO_2 nanosuspension.

4.2 Installation

In the installation step it has been evaluated the transport by lorry from the company, where the nanoTiO_2 self-cleaning coated float glass has been produced, to the installation site and the handling of glasses from lorry to private building. It has been considered the installation of a single glass with nanoTiO_2 coating side oriented toward outside.

4.3 Use

In the use phase nanoTiO_2 self-cleaning coated float glass has been considered for applications as windows, external windows, conservatories, etc. In according with Fujishima et al. [10] ten years it has been assumed to be the duration of nanoTiO_2 coating effects. In the study it has been assessed the heat gain during winter and summer seasons with application of nanoTiO_2 coating on external side. In particular, radiant heat originating from indoors in winter is reflected back inside, while infrared heat radiation from the sun during summer is reflected away, keeping it cooler inside. Furthermore it has been evaluated the benefict of nanocoating such as the reduction of NOx and VOCs concentrations. Finally, annual maintenance of glazing with only water and viscose fiber cloth it has been included.

4.4 End of life

In order to protect the human health and considering the uncertainty on the potential damage caused by nanoparticles, it has been assumed to make inert the glass through specific waste treatment (cover waste glasses with concrete and then bury the obtained concrete matrix). It is ongoing studies to assess different waste treatment scenario.

5 LIFE CYCLE ASSESSMENT

5.1 Goal definition

The goal of the study is to assess the environmental impacts of a nanoTiO_2 self-cleaning coated float glass over its entire life cycle in order to identify the hot spots of the system during the entire life cycle.

5.2 System, functional unit and function of the system

The system studied is a self-cleaning glass coated with nanoTiO_2 film to create a surface that remains cleaner for longer than conventional glass. A transparent coating on the external surface of the glass harnesses the power of UV rays and rain or water to break down airborne pollutions and grime. The function of self-cleaning is the applications for private buildings, such as traditional windows and curtain walls as well as glazings. For the aim of the present study, 1 m^2 of a single nanoTiO_2 self-cleaning coated float glass (size 1500 mm x 500 mm x 4 mm) is analysed.

5.3 System boundaries

The system boundaries cover the entire life cycle of the system analyzed, following the LCA approach. As can be seen in Fig. 1, the analysis includes the supply of all raw materials involved in the coating process, packing, installation and end of life. The production, maintenance and disposal of facilities as well as the environmental burdens related to the production of chemicals, packaging and other auxiliary materials are also included in the present study. Emissions into the air and water, as well as the solid waste produced in each step are all taken into account. The transportation to treatment facility of the solid wastes is also taken into account. For the studied system the following assumptions are hypothised:

- the transport of facilities, raw material, chemicals, materials for packaging is supposed with a scenario of 100 km from the producer to the customers, as is required by the environmental product declaration product certification (EPD) [11],
- the electricity energy production is assumed to be the Italian mix electricity energy created by Ecoinvent,
- the use of 99,97% efficiency HEPA (High-Efficiency Particulate Air) air filter during cutting, soaking in acetic acid and coating steps.
- the use of 95% efficiency PPE (*Personal protective equipment)* during coating, installation, use and end of life steps.

5.4 Impact assessment methodology

The analysis is conducted using the SimaPro 7.3.3 software and IMPACT 2002+ evaluation method to assess the environmental impacts. This impact assessment method covers more impact categories than other methods and includes more substances, but the following additions and modifications have been implemented in order to use a more representative index of the considered system:

- land use has been estimated using basic indicators of both land occupation and transformation. The *Transformation, to forest intensive, normal, Transformation, to forest intensive and Transformation, to arable* have been introduced.
- mineral extraction has been characterized considering some additional resources such as Silver, Gravel, Sand, Lithium, Bromine and water in ground derived from the category Minerals of Eco-indicator 99 method with the same characterization factors.
- radioactive waste category has been added, it has been evaluated radioactive waste and volume occupied by them considering the same charaterization and normalization factors of EPID 2003 method.
- emissions of titania nanoparticles in air and inhaled by worker or person who handling the nanocoating glass during the application, use and end of life phases. *Particulates, <100 nm* has been introducted in Carcinogens impact category with a charaterization factor previously calculated [12]. *Particulates, <100 nm (indoor)* has been introduced in a new impact category (Carcinogens indoor) with a new calculated charaterization factor.

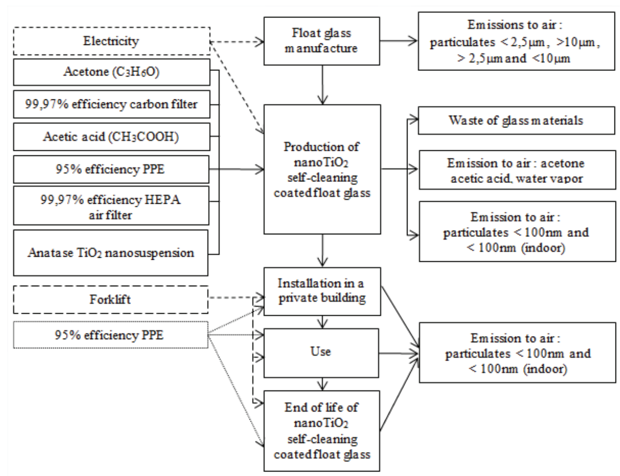

Figure 1: Flow chart of nanoTiO_2 self-cleaning coated float glass

5.5 Life cycle inventory

The compilation of inventory data was carried out using databases included in SimaPro 7.3.3 software. The ecodesign of industrial scale up production of self-cleaning glass coated with nanoTiO_2 film has been performed on lab data carried out by the experiments to determinate the optimized coating method. The remaining data have been obtained from specialised databases and literature such as devices, machineries, plants, internal transports, ordinary maintenance operations and all data regarding installation, use and end of life steps.

A selection of important data used in LCI (Life Cycle Inventory) of nanoTiO_2 self-cleaning coated float glass (1500 mm x 500 mm x 4 mm) is reported in Table 1.

Category	**Components**	**Quantity**	**Unit**
Energy input	Electricity	183,338	kWh
Materials I/O	Float glass uncoated	7431,21	g
	Acetone	197500	g
	Acetic acid	3,283	kg
	Water deionised	1,794	kg
	nanoTiO_2 suspension	4,375	g
Emissions to air	Particulates < 2,5 µm, > 10 µm and > 2.5 µm and < 10 µm	35,155	g
	Acetic acid	54,05	g
	Acetone	2,48E-3	g
	Particulates < 100 nm	5,07195	g
	Particulates < 100 nm (indoor)	558,87	µg
	Nitric acid	184,42	g
	CO_2	29,42	kg
Transports	Road	64117,2	kgkm
Waste to treatment	Disposal of to residual landfill particulates < 100nm captured by filter	0,302	g
	Acetone waste captured by filter	378,6	cm^3
	Acetic acid waste captured by filter	3,25	kg
	Disposal waste glass	6029,84	g
	Disposal to residual landfill of particulates captured by filter	936,158	g

Table 1: Inventory data of nanoTiO_2 self-cleaning coated float glass (size 1500 mm x 500 mm x 4 mm)

6 IMPACT ASSESSMENT AND CONCLUDING REMARKS

In Fig. 2 the environmental loads at the impact categories level of each single steps of 1 m^2 of nanoTiO_2 self-cleaning coated float glass (size 1500 mm x 500 mm x 4 mm) is reported. The analysis of the results highlights that the single score damage is 0,01473 Pt. The phases of the life cycle with the highest environmental burdens are the production (111%) and the end of life steps (10,55%). The results of the damage assessment show that damage to Human Health is due to the effects of inorganic emissions (101,64%) caused by NO_x to air (30,42%) particulates < 2,5 µm emissions (30,13%) and that are released during the production step, in particular in float glass uncoated manufacture and polished steps respectively. The effects on terrestrial ecotoxicity control overall Ecosystem Quality (52,87%) and the damage is mainly due to occupation, forest, intensive, normal (19,6%), aluminum in air (14,7%) and aluminum to soil (13,51%). For the first substance the process that contributes to the highest impact is the final glass treatment in end of life step, instead for the other emissions is due to soaking phase in the production step. The damage to Climate Change is generated by the emissions of 39,22 kg $CO_{2\ (eq)}$, which are mainly released during the production step. The consumption of crude oil (48,18%), natural gas (16,6%), and uranium (15,9%) in energy supply processes affects the Resources category, where the depletion of non-renewable energy resources produces the most damage (99,5%) and the production step, in particular the soaking of glass is the process that major affects this damage category. The volume occupied by final repository for low-radioactive (65,25%) and radioactive waste (34,75%) determinate the main impact of Radioactive waste damage category due to electric energy consumptions of production step. The emissions of particulates < 100 nm inhaled by worker affect the Carcinogens indoor category and the final glass treatment in end of life step produce the highest damage. In according with ecodesign approach the production choices carried out during the study have been done to optimize the environmental burdens.

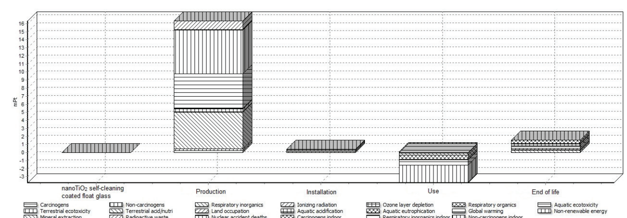

Figure 2: Evaluation by impact categories of 1 m^2 of nanoTiO_2 self-cleaning coated float glass

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